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Volume 5 2019

Including articles from the AGM 2018 Geoff Brown Memorial Lecture, the 'Music of the Earth' Symposium 2018 lectures (Worcester University), OUGS Members' field trip reports, the Annual Report for 2018, and the 2018 Moyra Eldridge Photographic Competition Winning and Highly Commended photographs

Edited and designed by:
Dr David M. Jones
41 Blackburn Way,
Godalming, Surrey GU7 1JY
e-mail: proceedings@ougs.org

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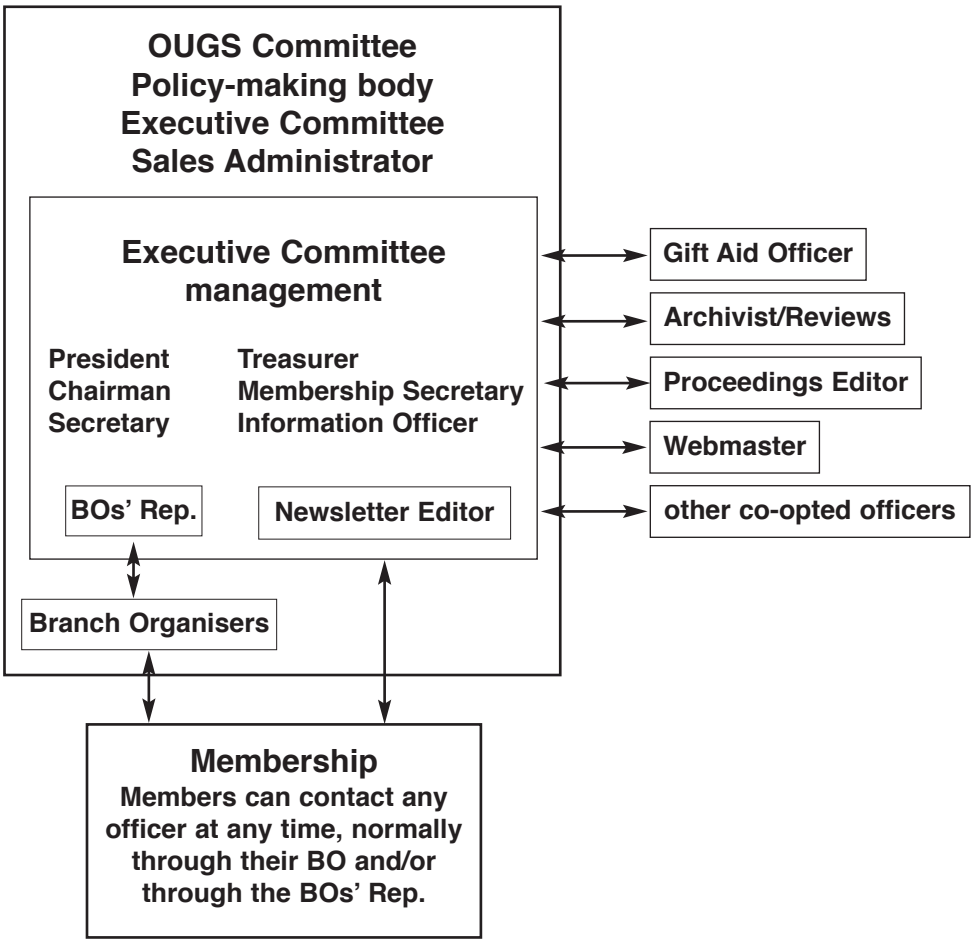


Editorial:

Dear readers,

This year is a momentous one for the Open University. It is celebrating its 50th anniversary. The Open University Geological Society has been associated with the OU and with its various permutations of Geology and Earth Science faculties almost as long — since 1972.

The establishment of the OUGS at Shap Wells in Cumbria was indeed celebrated in our 46th year, at its 2018 AGM at Shap Wells by the unveiling of the slabs of Shap Granite re-mounted on the wall outside the newly refurnished hotel at its main entrance on the 21st of April last year.

Our 46th OUGS Annual Symposium was held at the University of Worcester in August 2018. As if in honour of this, and of its musically themed title — Music of the Earth — every speaker, including two who were unfortunately unable to deliver their lectures at the Symposium owing to unexpected illnesses, kept perfect time with the group and delivered his or her article for this issue of our publication by the requested deadline — a first in the tenure of this long-suffering Editor! :-) And for which he heartily thanks them all.

So also was the prompt delivery by then post-graduate student Jonathan Moles, who spiritedly stepped in to deliver the annual Geoff Brown Memorial Lecture at our 2018 AGM when veteran volcano researcher Dr Dave McGarvie, the originally scheduled speaker, was unable to attend owing to injuries sustained in his exciting pursuit of volcanic processes in Chile.

Jonathan, I am pleased to say, recently sent me an e-mail to tell me that his viva went well and that he is soon to be, officially, Dr Moles — another tribute to the achievement in the OU's provision of education.

So, for your reading pleasure, esteemed Members, in this issue we have for you the Geoff Brown Memorial Lecture, this year on the 'tool' of volcanic ash, and 12 articles ranging around the geology of the Malverns, of Worcestershire, Hertfordshire and Mid-Wales, of Britain's Midland Platform, and of Malvern waters, building stones and public geology outreach; plus, the Triassic rise of dinosaurs and the importance of water in aeolian systems — shall we call these 'the outliers'?!

Our President, Dr Schwenzer, has given us her first Symposium 'summing up', including a clever musical metaphor in the spirit of the Symposium's theme. Not only is our President's middle name a solid one — Petra — but it is also my understanding that she drives a car on Mars!

Also in this issue we have two OUGS Member articles, one from our ever-active and informative Duncan Woodcock, on lamprophyres; and a field trip report by 18 Members on their OUGS trip to Hawai'i.

Plus, there are 14 more book reviews.

As always, I wish you happy reading.

— David M. Jones, OUGS Proceedings Editor

Achnowledgements
The Editor would like to give his sincere thank-you to fellow OUGS Members who gave him invaluable help with all aspects of this issue of the *OUGS Proceedings*: to all the authors for their cooperation and timely responses to my many editorial queries; to OUGS Chairman Sue Vernon and OUGS President Susanne Schwenzer for their advice and encouragement; to Ireland Branch Member Isabel O'Brien and OUGS Secretary Don Cameron for their diligent proofreading; and to OUGS Family Member Anne Jones for her suggestions and advice regarding layout and design.

Errata — Proceedings 4 2018

Embarrasingly, but seemingly not spotted until Septemebr 2018, the title page of *Proceedings* 4 2018 has an error! The Symposium was in Edinburgh, not in Milton Keynes (which was where the AGM was held).

Eagle-eyed readers of last-year's *Proceedings* will have spotted that on page 35 the penultimate line of the first paragraph should be 'borders', not 'boarders'. And on [page 126] the caption for Anna Saich's photograph of Kentish Ragstone should read 'a stone mason'.

The Editor apologises for these errors.

I would also like to correct — and apologise for — an editorial mis-interpretation in the last sentence of page 10 of the issue. The printed version reads: "But, paradoxically, within each tract most of the strata young northwards owing to local reverse folding." This should read: "But, paradoxically, within each tract most of the strata young northwards (with local reversals due to folding)." [For what it is worth, this unfortunate error highlights the importance of meeting copy deadlines established at the end of OUGS July–August Symposia. These are set as the end of December of the year in which the Symposium took place. Unfortunately, in this case the article was delivered more than two months late, and three days *after the Editor's print-file deadlines to the printer*, necessitating a request to the printer for extra time and leaving the Editor one day to edit and do page layout for this article, and then to make layout adjustments and to finalise contents and cover compositions before the issue could be sent to the printers.]

OUGS AGM 2018 Geoff Brown Memorial Lecture

Volcanic ash — a research tool that goes far beyond volcanoes

Jonathan Moles

PhD (awarded subject to minor corrections), The Open University

Introduction

After breaking his leg and ankle on Quetrupillán volcano in Chile, Dave McGarvie (OUGS President 2011–12) asked that I take over his role as presenter of the Geoff Brown Memorial Lecture at the OUGS AGM 2018. This gave me the opportunity to talk about one aspect of my PhD research — layers of volcanic ash — at the final stage of my project. Under the supervision of Dave and other past presenters of this lecture — Sarah Sherlock and John Stevenson — I have been working on Icelandic volcanoes to uncover evidence of past glacial environments.

In this article I will explain how volcanic ash layers are a valuable research tool across multiple disciplines. As well as informing us of the processes of ash dispersal during volcanic eruptions, these deposits can be used as time markers in studies of past environments and human migration.

The production and dispersal of volcanic ash

Volcanic ash is made of fragments of volcanic rock less than 2mm in diameter, typically composed of volcanic glass (quenched magma) with a minor amount of crystals and other pulverised rock fragments (Fig. 1). A broader term — tephra — similarly refers to material blasted out of a volcano, but also encompasses larger fragments such as lapilli (2–64mm in diameter) and bombs (>64mm in diameter). Ash is produced during explosive volcanic eruptions when magma is ripped apart by rapidly expanding gases. Commonly, these gases are initially dissolved in the magma and escape violently due to decompression, like opening a bottle of fizzy drink. Alternatively, explosions can occur when water bodies such as lakes or groundwater interact with the erupting magma. Water expands by 1,600 times when it turns to vapour, producing an explosion that can shatter magma into tiny fragments of ash.

Explosive eruptions thrust volcanic ash into the atmosphere very rapidly, with material being ejected from the vent at supersonic speeds. These plumes can rise up into the stratosphere as buoyant mixtures of hot ash and gases. On reaching an altitude of neutral buoyancy, the plume stops rising and is carried away by the wind. Powerful winds in the upper troposphere and the stratosphere can transport ash over vast distances. During the eruption of Cordón Caulle (Chile) in 2011, an ash plume circumnavigated the globe to arrive back in the skies above Chile two weeks after the eruption began (Fig. 2).

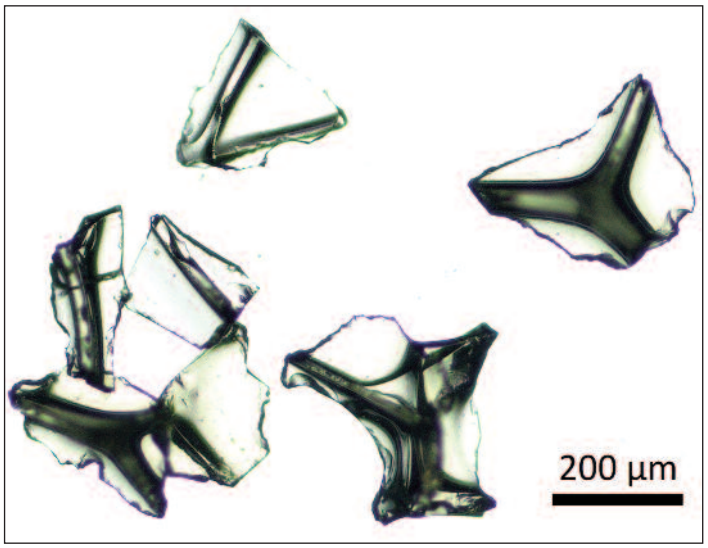
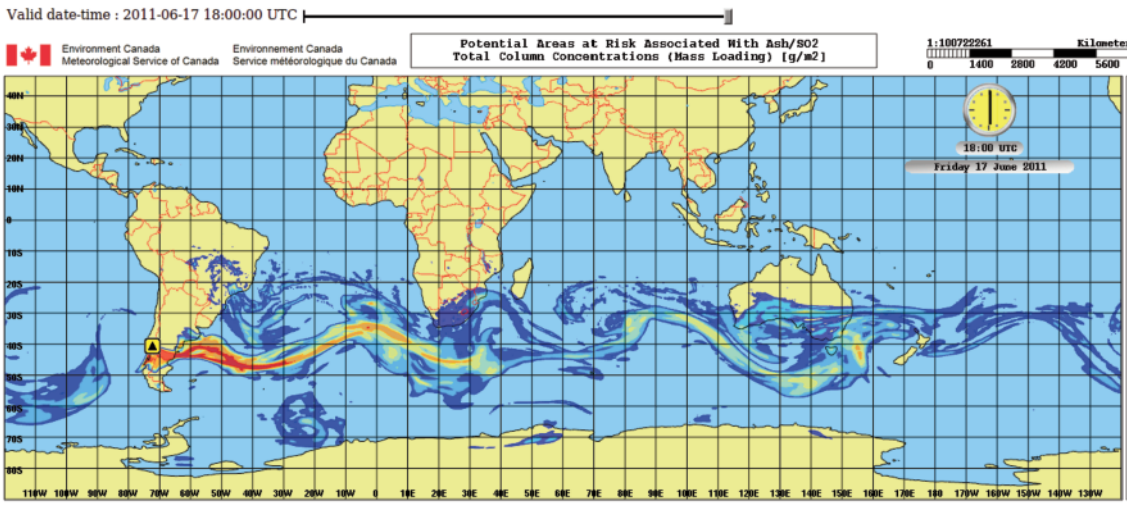


Figure 1 Volcanic ash viewed under a microscope. This ash is composed of rhyolitic volcanic glass and was collected 30km from the source volcano — Torfajökull — in Iceland. The shape of these ash particles indicates that the erupting magma was rich in gas bubbles: platy surfaces were formed at bubble walls and cuspate structures were formed at bubble junctions (photo © Jonathan Moles).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Environment Canada
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18:00 UTC
Friday 17 June 2011

Figure 2 Long-range dispersal of ash from Cordón Caulle in 2011. Aviation was disrupted in South America, South Africa, Australia and New Zealand. Map produced by the Meteorological Service of Canada, showing the predicted concentration of ash according to the MLDP0 dispersion model (© Meteorological Service of Canada, here reproduced for non-commercial use only).

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Figure 3 Buildings inundated by a lahar following the 1982 eruption of Galunggung volcano, Indonesia. Ash produced by the eruption had a destructive impact on the ground and in the air (photo by Robin Holcomb, © U.S. Geological Survey, Public Domain — here reproduced for non-commercial use only).

Volcanic ash has a bad reputation, especially following the disruption to aviation caused by the 2010 eruption of Eyjafjallajökull volcano in Iceland. To ensure safety during this eruption, aircraft initially avoided all areas of volcanic ash, though the rules were later relaxed to allow flights in airspace with a low concentration of ash (<4g/m^3). The caution shown by the authorities was for good reason, given the destructive effect of ash on aircraft. This hazard was demonstrated by British Airways Flight 9, which flew through the ash plume of Galunggung volcano in Indonesia in 1982. All four engines of the Boeing 747 shut down due to ingestion of ash. The ash scratched the windows of the plane, blocking the view of the pilots, and clogged up exterior sensors. Miraculously, after the aircraft had lost two-thirds of its initial altitude, the pilots were able to restart the engines and clear the mountains to land at Jakarta airport. Ash also has an impact on human health, agriculture and water supplies, and can trigger devastating mudflows (known as 'lahars') when mixed with rainwater or snowmelt (Fig. 3).

Making good use of volcanic ash

The widespread dispersal and fallout of volcanic ash leads to the deposition of ash layers in a variety of settings, such as seafloor sediments, peat bogs and ice sheets (Fig. 4). In recent years, small quantities of ash have been found thousands of kilometres from their source volcanoes. For instance, ash from volcanoes in the Pacific 'Ring of Fire' (specifically Mexico, the Cascades, Alaska and Kamchatka) have been discovered in peat bogs in Ireland (Plunkett and Pilcher 2018). Such deposits ('cryptotephras') are not visible to the naked eye and must be carefully extracted from their host material.

Despite the challenge of finding volcanic ash layers, they are highly prized as marker horizons that precisely record the eruption event in multiple depositional settings. An ash layer is an isochron that represents a specific moment in time across every setting where it is found. Depositional sequences can therefore be stratigraphically linked using shared ash layers: a relative dating technique known as tephrochronology. In order to establish correlations across multiple sequences, each ash layer must have unique identifiable features. Correlations are typically established by analysing the geochemistry of the fragments of ash. In most cases, the ash produced during one eruption will have a distinctive geochemical 'fingerprint' that can be used to identify it wherever it is found. It is important that the geochemical evidence is supported by the stratigraphic context of the ash layer and its physical features.

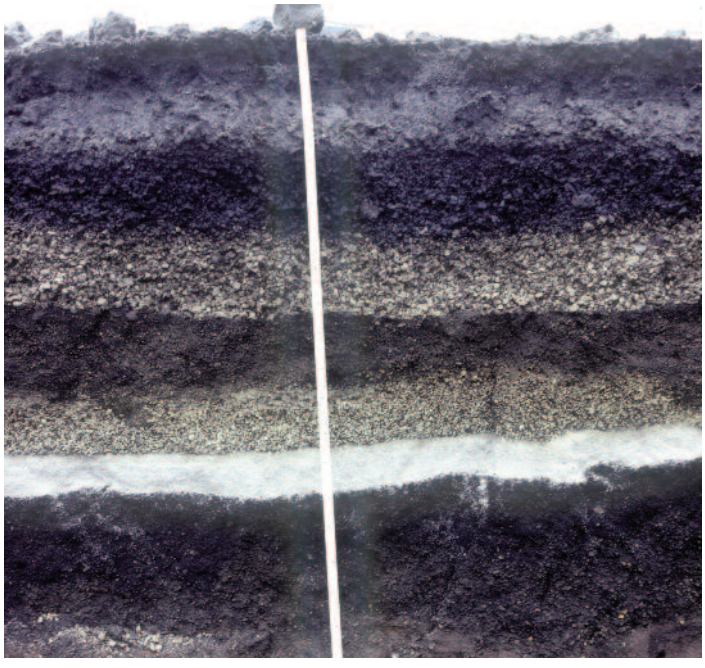
By correlating ash layers across great distances, a vast amount of stratigraphic information can be pooled together. In the rest of this article, I will describe just a few applications of this technique.

Ash dispersal from a subglacial volcano

I have recently been researching a little-known type of volcanic eruption: rhyolitic eruptions at subglacial volcanoes. It had never been shown that a rhyolitic eruption under an ice sheet could breach the ice surface and produce widespread ash deposits. I set out to find the source of a widespread ash layer — the rhyolitic component of North Atlantic Ash Zone II — to see if the eruption was sourced from a subglacial volcano. It had already been identified that the ash came from an Icelandic eruption (Sigurdsson 1982), and that the eruption occurred during the last glacial period (*c.* 55,000 years ago; Svensson *et al.* 2008) when Iceland hosted much more ice than today. The ash was deposited on the Greenland ice sheet, where it forms a visible layer (Ram and Gayley 1991), and on sea ice that surrounded Iceland. Break-up and southward rafting of this ash-laden sea ice led to dispersal of the ash across a large area of the North Atlantic, as far as 2,300km from Iceland (Ruddiman and Glover 1972; Fig. 5, *opposite*).

By comparing the age and geochemistry of the ash in marine sediments with deposits in Iceland, I was able to identify Torfajökull volcano as the source of the eruption. Torfajökull volcano covers an area of 450km^2 in southern Iceland and, unusually, is largely composed of rhyolite. During the eruption in question, a large volume (approximately 18km^3) of ash and lava (known as the 'Ring Fracture Rhyolites') was emplaced at

Figure 4 Layers of tephra deposited near Torfajökull volcano in Iceland. The visible section is 1m thick. Some ash layers can be traced thousands of kilometres from their sources, though they are typically invisible at these distances (photo © Dave McGarvie, reproduced with permission).



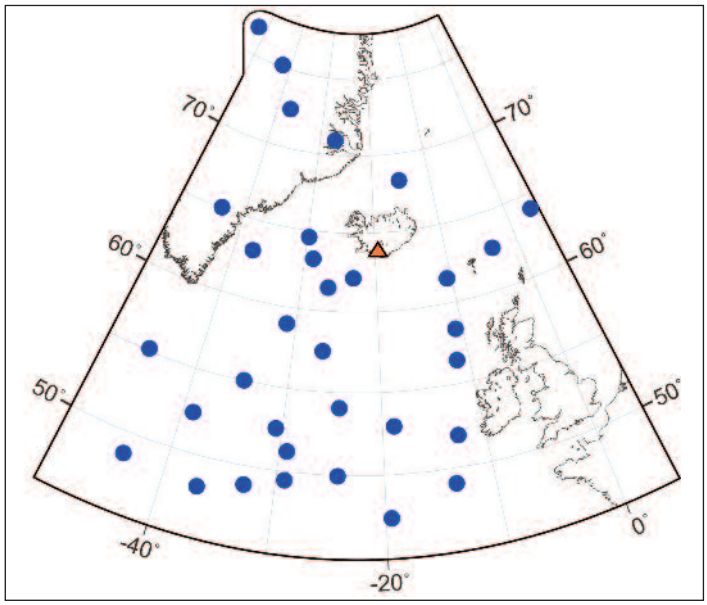


Figure 5 Map of reported occurrences of North Atlantic Ash Zone II (blue circles) in marine sediment cores and Greenland ice cores. Atmospheric dispersal of the ash from south Iceland (orange triangle) led to fallout on the Greenland ice sheet and on sea ice. Southward rafting of the sea ice then carried the ash across a wide area of the North Atlantic (image © Jonathan Moles).

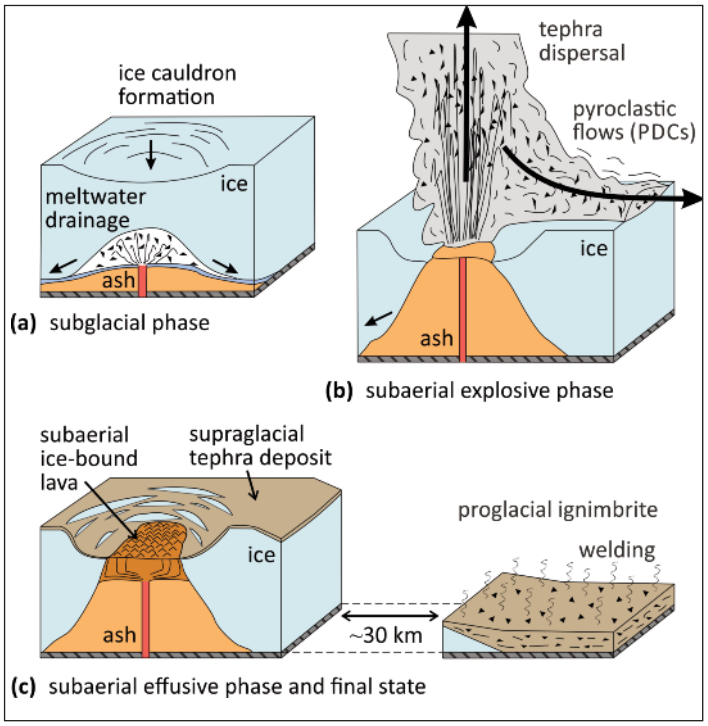


Figure 7 Model of rhyolite tuya formation modified from Tuffen et al. *(2002). Despite the eruption commencing in a subglacial environment (a), breaching of the ice leads to a subaerial explosive phase of the eruption (b). The eruptive products that remain at the vent were confined by ice to form a steep-sided tuya (c), but ice did not prevent the widespread dispersal of tephra and the emplacement of welded ignimbrite (image © Jonathan Moles).*

Torfajökull, and an ignimbrite — the Thórsmörk Ignimbrite — was deposited *c.* 30km to the south-west of the volcano. When the ignimbrite was deposited by pyroclastic flows, the ash particles were hot enough to weld together, forming solid rock (Jørgensen 1980).

Previous work on the Ring Fracture Rhyolites showed that these deposits had been confined by ice during the eruption, forming steep-sided piles of ash and lava known as 'tuyas' (Tuffen *et al.* 2002; Fig. 6). The height of the tuyas indicates that they were emplaced into an ice sheet at least 400m thick (McGarvie *et al.* 2006). Now that the tuyas have been correlated with a widespread ash layer and an ignimbrite, it is clear that the eruption breached the ice sheet and formed a significant ash plume (Fig. 7). Pyroclastic flows travelled across the surface of the ice sheet and beyond, in order to deposit the ignimbrite in an ice-free area 30km away. It appears that the presence of an ice sheet does not restrict the potential for widespread ash dispersal during rhyolitic eruptions.

Figure 6 The flat-topped edifice of Kirkjufell (middle distance), which forms part of the Ring Fracture Rhyolites of Torfajökull volcano, Iceland. The products of the eruption were confined by an ice sheet >400m thick, leading to the formation of a steep-sided tuya (photo © Dave McGarvie, reproduced with permission).

Past glacial environments and climate

The Ring Fracture Rhyolites and the Thórsmörk Ignimbrite provide a unique record of the minimum thickness and extent of ice in southern Iceland at the time of the eruption. This information is most useful when the climate at the time of the eruption is also known, but it is difficult to precisely date volcanic eruptions relative to a rapidly fluctuating climate. According to the record derived from the Greenland ice cores (Dansgaard *et al.* 1993), the climate during the last glacial period was punctuated by sudden warm episodes ('interstadials'), each followed by a transition back to cold conditions ('stadials'). Radiometric dating techniques are not precise enough to date the eruption — and the associated ice reconstructions — to a particular stadial or interstadial. This is where the ash layer produced by the eruption — North Atlantic Ash Zone II — becomes a valuable tool. It marks the timing of the eruption directly within the Greenland ice cores, providing a link between the eruption in Iceland and the climate record in Greenland. Now we can pinpoint the timing of the eruption to the cooling transition at the end of Greenland Interstadial 15.2, and place the ice estimates in their precise climate context.

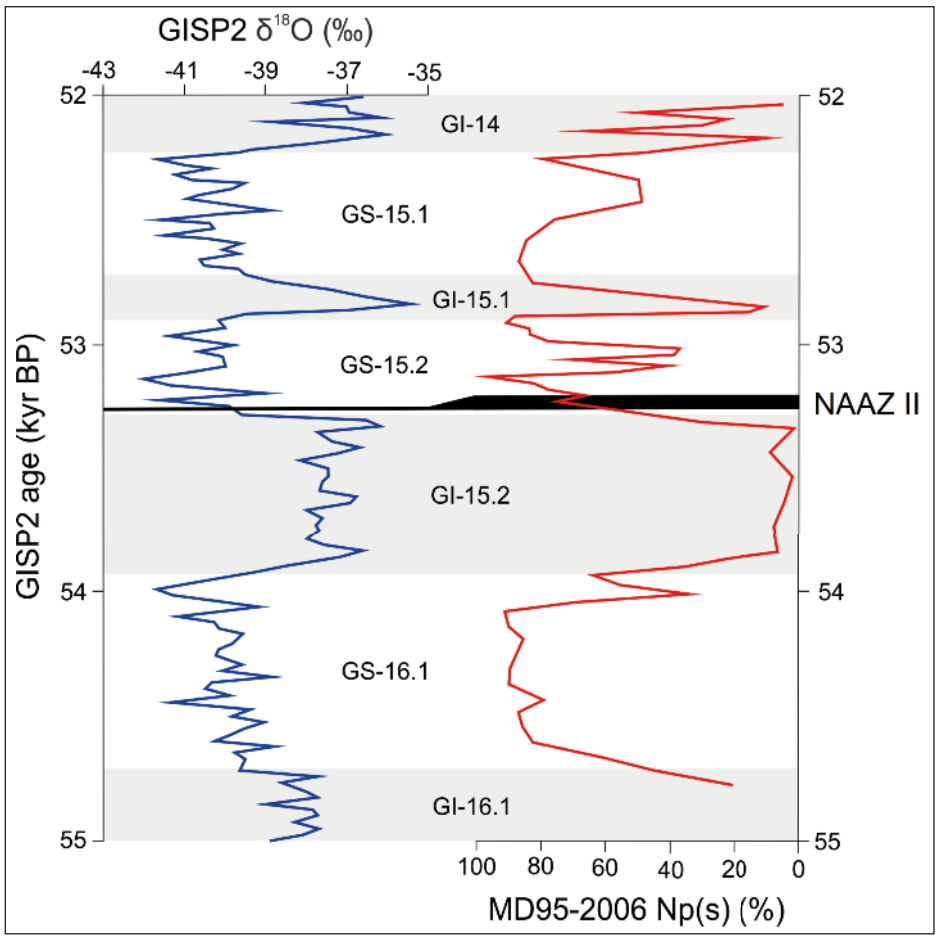


Figure 8 Precise synchronisation of ice core (left) and marine sediment (right) palaeoclimate records using North Atlantic Ash Zone II (NAAZ II; figure modified from Austin et al. *2004). The ash layer is present in both the GISP2 (Greenland Ice Core Project 2) ice core and the MD95-2006 sediment core, enabling researchers to link together the palaeoclimate records derived from these cores. Greenland Interstadials (GI; shaded in grey) are periods of relatively warm climate and Greenland Stadials (GS) are relatively cold. By linking these climate records using NAAZ II, Austin et al. (2004) demonstrated that the cooling in climate at the end of GI-15.2 was synchronous across the North Atlantic region (image © Jonathan Moles).*

The presence of ash from the same eruption in Iceland, the Greenland ice sheet and North Atlantic marine sediments enables us to make a direct comparison of palaeoenvironmental records from each of these settings. We can therefore build up a picture of the climate and associated environmental conditions from terrestrial, marine and ice settings using volcanic ash as a time marker. For example, the ash layer can also be used to compare the climate in Greenland with the patterns of sea ice formation and melting in the North Atlantic, which are indicated by the distribution of the ice-rafted ash in marine sediments.

In one study by Austin *et al.* (2004), North Atlantic Ash Zone II was used to assess the relative timing of abrupt climate change in the atmosphere and in the ocean. To do this, climate records were sourced from a Greenland ice core and from a core of marine sediment taken 155km west of Barra (Outer Hebrides). The ratio of oxygen isotopes in the ice core ($\delta^{18}O$) is a proxy for the atmospheric temperature in Greenland, and the relative abundance of a foram — *Neogloboquadrina pachyderma* (sinistral coiling; Np(s)) — is used as a proxy for sea surface temperature in the sediment core. Using the ash horizon found in both of these cores, the two climate records can be linked together, to see if changes in climate happened at the same time in different locations. It was found that the shift in climate at the end of Greenland Interstadial 15.2 was synchronous in both climate records (Fig. 8), suggesting that the climate changed at the same time across the North Atlantic region in both the atmosphere and the ocean. Volcanic ash layers are a very precise way of linking these records and are a valuable tool for understanding how climate changes and what drives those changes.

Timing of human colonisation

Volcanic ash layers are just as valuable in archaeological studies as they are in studies of past environments. In fact, these fields of research are often combined in order to study both the actions of humans in the past and the associated impact on the environment. In New Zealand, a layer of volcanic ash — the Kaharoa tephra — is a useful marker that was deposited around the time of the first human settlement of the islands (Newnham *et al.* 1998). The first settlers migrated from Polynesia surprisingly late: the eruption has been dated to 1314±12 AD (Hogg *et al.* 2003) and widespread evidence of human activity is only found above the ash layer. The deposits above the ash are rich in charcoal, and pollen records show a decline in tall trees, indicating a period of deforestation by burning (Lowe 2011). Just below the ash layer, the earliest evidence of humans is a seed case that has been gnawed by a Pacific rat (Wilmshurst and Higham 2004). As this rat species is unable to swim long distances, it is believed that humans introduced it to New Zealand. The current best estimate for the first settlement of New Zealand is *c.* 1280 AD.

In Iceland, multiple ash layers preserved in soils can be used to assess the timing, as well as the rate, of human colonisation (Fig 9, *opposite*). Due to the frequency of volcanic eruptions, ash layers are commonly found at archaeological sites and can be used to date the structures built by Norse settlers. Many structures even have ash layers incorporated into them, because turf was used as a building material. The following summary is derived from a review of archaeological sites by Schmid *et al.* (2017).

A volcanic eruption dispersed ash across Iceland in 877±1 AD (the Landnám tephra), roughly the same time as the first permanent settlement of the island (Gaelic monks and Norse explorers had visited Iceland before, but probably not as permanent residents). Only two archaeological sites, restricted to the south-west corner of the island, have evidence of human occupation before this ash layer. However, by the time of the next major eruption in 939 AD (Eldgjá: the largest eruption in the human history of Iceland), settlers had colonised most of the inhabited areas of Iceland. Thousands of people are thought to have moved from Norway to Iceland during the period between these eruptions,

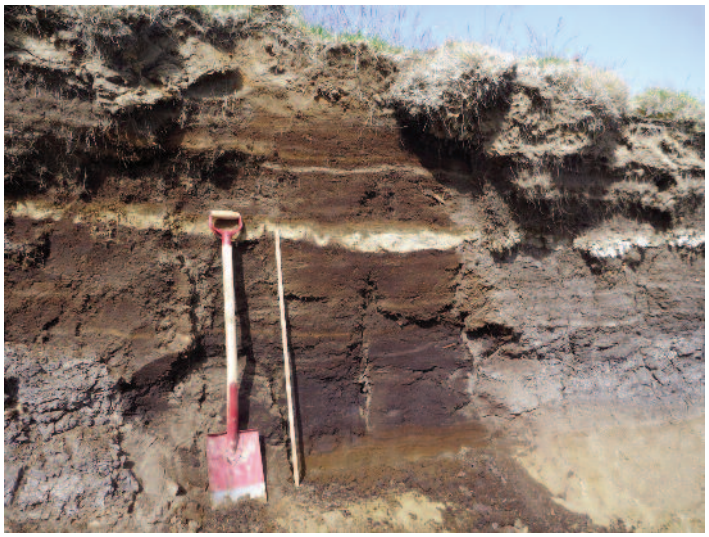


Figure 9 Ash layers preserved in a soil section in north Iceland. The prominent white layer is probably sourced from a major eruption of Hekla volcano c. *4,200 years ago. Ash layers are commonly used to date archaeological evidence in Iceland, with widespread indicators of human occupation only found above the Landnám tephra (877±1 AD) (photo © John Stevenson, reproduced with permission).*

and the Alþingi — the Icelandic parliament — was founded in 930 AD. It appears that Iceland was fully settled before the smaller-scale Viking expansions to Greenland (986 AD) and North America (*c.* 1000 AD).

The far-reaching use of volcanic ash has been demonstrated at an archaeological site in the Lofoten Islands, Norway (Fig. 10). Here, remains of a Viking boathouse are sandwiched between two ash layers, which can be used to date the main period that the boathouse was in use (Balascio *et al.* 2011). The ash layer that overlies (i.e. post-dates) the boathouse is sourced from an eruption of Hekla volcano, Iceland, in 1104 AD. The ash layer that underlies (pre-dates) the remains has been identified in Greenland ice cores, where it has been dated to 846–847 AD. Since the underlying ash layer was found at the archaeological site, the source volcano has been identified as Mount Churchill in Alaska, 5,500km away (Jensen *et al.* 2014). The ability to trace dated ash layers over such large distances makes it possible to precisely compare cultural and environmental histories across entire oceans and continents.

Conclusion

Understandably, volcanic ash has negative connotations for many people. But for researchers in a wide range of disciplines, volcanic ash layers from past eruptions are a valuable tool. This article has described only a small number of the ways in which volcanic ash layers can aid our understanding of the past. Deposits of volcanic ash are increasingly being discovered several thousands of kilometres from their source volcanoes, and researchers are in the process of developing innovative techniques for studying them. From studies of ancient ice sheets in Iceland to human migration in the Pacific, volcanic ash is a research tool that is going far beyond volcanoes.

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Figure 10 Reconstructed Viking chieftain's house at the Borg archaeological site, Lofoten Islands, Norway. A number of Viking Age boathouses are associated with the site. Excavations at one of the boathouses revealed volcanic ash layers sourced from Alaska and Iceland, which constrain the boathouse's main period of use to between 846 AD and 1104 AD (photo © Jorge Andrade, licensed under a Creative Commons Attribution license, here reproduced for non-commercial use only).

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OUGS Symposium, Worcester 2018: Music of the Earth

The Worcester Region: geodiversity, geoconservation and geoeducation

Ian Fairchild

Herefordshire and Worcestershire Earth Heritage Trust, Geological Records Centre, University of Worcester, Henwick Grove, Worcester WR2 6AJ
and Emeritus Professor, School of Geography, Earth and Environmental Sciences, University of Birmingham B15 2TT

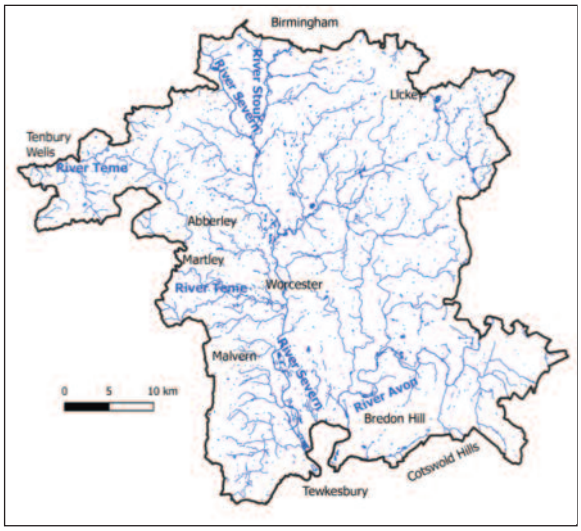

Figure 1 Physiography and places in Worcestershire.

Figure 3 Precambrian rocks at Worcestershire Beacon, Malverns (photo credit: Ian Fairchild/EHT).

Introduction

The county of Worcestershire (Fig. 1) is characterised by diverse geology and landscapes from the Precambrian igneous rocks of the Malvern Hills to the diverse Quaternary deposits flanking the uplands and river valleys alike. The centre of the county is dominated by the Severn river valley largely cut into Triassic clastic sediments of the Worcester graben. The Severn is joined by its right-bank tributary of the Teme and left-bank tributaries of the Stour and the Avon. The present-day courses of both the Severn and the Teme originate from late Quaternary river-capture events: the Ironbridge gorge and the region near Tenbury Wells, respectively. To the south-east of the county lies the edge of the Jurassic Cotswold escarpment, including the outlier of Bredon Hill south-west of Evesham (Fig. 2). The distinct small escarpment of harder lithologies around the Triassic-Jurassic boundary traverses the Severn and Avon vales and is repeated by faulting. In the far north of the county lies the NNW–SSE Lickey line of deformed Ordovician quartz sandstones overlying Precambrian volcanics and in turn overlain by Lower Silurian sandstones and Coal Measures. The southern part of the western border of the county is marked by the Malvern line (Fig. 3), a long-lived tectonic lineament, today marked by a line of Neoproterozoic intrusive and volcanic rocks, faulted against the Triassic to the east and variably faulted and unconformably overlain by Cambrian and especially Silurian strata to the east *(Pharaoh, this volume p35)*. The Malvern line continues north to Martley, where complex compressive Variscan structures are present, and on to the Abberley Hills *(Barclay* et al*., this volume p21)*.

Figure 2 View across the Severn valley from the Banbury Stone (cemented Quaternary rift-fill breccia in Jurassic limestones), including the Malverns (top left) (photo credit: Adam Stanford/EHT).

This OUGS Symposium had a theme of *Music of the Earth*. Worcestershire has an association with Edward Elgar, who not only lived in the county during various periods of his life, but was also born in a cottage in Lower Broadheath, just to the west of Worcester (Fig. 4). The cottage was the basis for the establishment of the Elgar Birthplace Museum, now taken over by the National Trust. Elgar famously dreamed of creating "something great" during visits to the reedy banks of the Severn as a youth.

Figure 4 Music of the Earth. The Elgar birthplace: cottage and bust of Elgar at Lower Broadheath near Worcester.

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A musical metaphor is also provided by the rhythm of Milankovitch forcing of the successive ice ages and more subtle lithological variations in the Lower Jurassic strata of the area.

Local geoheritage and the Earth Heritage Trust

The Worcester region has been the centre of a wide range of activities by both professional and amateur geologists to document and disseminate the diversity and heritage of our sites. A prominent organisation over the last 20 years has been the Herefordshire and Worcestershire Earth Heritage Trust (HWEHT; http://www.earthheritagetrust.org/pub/). The Trust was set up in 1996 at the Geological Records Centre located at the University of Worcester. This followed the creation of the Regionally Important Geological & Geomorphological Sites (RIGS) scheme by the Nature Conservancy Council (now Natural England) in 1990. In 1998 the Trust organised and ran the first UK RIGS Conference for county RIGS groups, held at the University of Worcester.

In 2000 the Trust joined several neighbouring geological conservation groups or trusts to form a regional association called the Western Association of RIGS Groups. Following the success of this project, the groups reorganised and in May 2003 renamed the association 'The Geology Trusts', now a national body. Natural England subsequently renamed RIGS as Local Geological Sites (LGS), but the sites still have the same status and protection through the planning system.

Over the years the HWEHT has published a large number of guides to local geology. Currently more than 35 are available, many of which are in the *Explore* series in which readers are taken on a short, self-guided walk (or drive) explaining the geology along the way.

In 2003 the Trust was working with partners to plan and organise the formation of the Abberley and Malvern Hills Geopark and in an extraordinarily active period over the next few years also ran a large number of projects funded by the Aggregates Levy Fund, the National Lottery, the Environment Agency and other sources. HWEHT become incorporated as a charity in 2011. Although money is much tighter these days, a continued stream of funding has been maintained. Several examples of projects and longer-term initiatives are described below, illustrating the range of geology in the local region.

Figure 5 The recumbent overfold in Ordovician Lickey Quartzite at the Barnt Green Road quarry, Lickey Hills as seen 1884, and thanks to continued clearance work, in 2016 (photos: C. J. Watson and Ian Fairchild/EHT).

Local geological sites

The designation and conservation of sites (formerly known as Regionally Important Geological Sites, now simply local geological sites or LGS) is a core purpose of the HWEHT, but there remains no specific funding stream to support this activity. The Trust has designated 90 sites in Worcestershire complementing a much smaller number of Sites of Special Scientific Importance (SSSIs), which are the statutory responsibility of Natural England. LGS, on the other hand, have more marginal protected status, but a proactive approach by the Trust and good relations with the County Council ensures that these sites are considered whenever planning applications, Local Development Plans and other planning instruments are considered. Over the years, there have been several spatial databases used to record sites and the latest version offers a portable design that it is hoped will be made available to interested parties outside Herefordshire and Worcestershire in 2019.

The Champions project (2008–12), funded by the Heritage Lottery Fund, was a pioneering and successful attempt to mobilize local interest in conservation of geological sites. Originally 19 locales were selected, of which 17 were the locations of significant conservation activity (9 in Worcestershire) and even in 2018, active site conservation led by the network of volunteer Champions continues. For example, a particularly active group has carried out extensive work in the Lickey Hills (Fig. 5) on the southern fringes of Birmingham and significant geological information has been made available to the public through leaflets, information boards and guided tours. More information is at http://ehtchampions.org.uk/ch/.

The Malverns are a classic area in British geology, and here geoconservation has been greatly assisted in recent years by the support of the Malvern Hills Trust (formerly the Malvern Conservators) and the Malvern Hills Area of Natural Beauty. Small focused grants over the last few years have enabled the Trust to organise groups of volunteers, and sometimes employ professional contractors, to recover the value of sites by removing vegetation and loose rock debris. A rolling programme focused on key sites continues (Bryant 2018). Awareness of Malvern geology is facilitated not only by notice boards and leaflets, but also by displays in the GeoCentre (http://www.geocentre.co.uk/), which includes a café and geological exhibits close to the Wyche cutting on the Malvern ridge.

The Geopark and the Geopark Way

Oversight of the geopark is now provided by a consortium — the Abberley and Malvern Hills Geopark Forum (http://geopark.org.uk/pub/). The Geopark covers parts of four counties, with a central spine along the Malvern-Abberley axis, and has recently been enlarged to include the Woolhope Dome in Herefordshire. The Earth Heritage Trust developed the award-winning 109-mile long footpath, *The Geopark Way*, which runs

from Bridgnorth in Shropshire through parts of Worcestershire and Herefordshire to Gloucester. It remains the only long-distance route designed to engage the walker with the rocks and landscape en route. A second edition to the guide to the Geopark Way will be published early in 2019 and negotiations are advanced with the Ordnance Survey to include the Way on their maps. It is recognised that Geoparks and the Geopark Way can be an important stimulus to tourist activity and hence local economic development, and this has been achieved primarily through voluntary activity, given the lack of national or local authority support in recent years. The Geopark Forum coordinates a programme of summer activities (Geofest) that are centred around stimulating interest in local geology and artisans.

A Geo-Village

Over the past few years, a highly active group of amateur geologists with some professional guidance have built a strong presence in the village of Martley, receiving European funding and founding the Teme Valley Geological Society. Members have been active in clearing local geological sites, excavating new temporary exposures of the complex structures along the Malvern line, running an active programme of activities, and hosting many visiting societies, attracted by the unusually diverse local geology. A particular novel development is their identification of the concept of a Geo-Village, defined (http://www.geo-village.eu/) as "a community that has distinctive geology within its bounds, has a policy of locally managed geological discovery and conservation, has developed a viable educational offer for both school pupils and adults and is using its geological assets in support of the local economy" *(Cropp, this volume p29)*.

Building stones

A major project led by the HWEHT, *A Thousand Years of Building with Stone* (Fig. 6), was carried out in the period 2013–17, and funded mainly by the Heritage Lottery Fund. Its key aims were to rediscover local building stone quarries, research the skills, techniques and people involved in exploiting this resource, raise awareness and appreciation of local stone, and to provide local people with a sense of place *(Andrew, this volume p13)*. These aims were amply realised. The final aim was to create a database (Fig. 7) linking stone to quarries and particular buildings, which is being maintained for at least 10 years and can be found at www.buildingstones.org.uk. The database plots sites both of buildings and quarries on a base map and includes site details and photographs. The database covers Herefordshire and Worcestershire, but in principle could be extended geographically. This work, to which large numbers of local people with local knowledge have contributed, complements and significantly amplifies the building stones resources developed nationally by the British Geological Survey (see: www.bgs.ac.uk/mineralsUK/buildingStones/home.html).

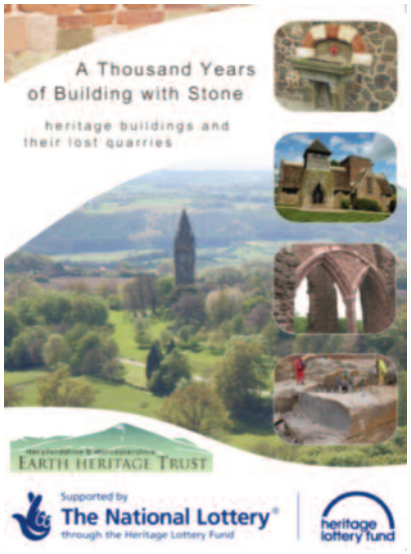

Figure 6 Flier for the Heritage Lottery-funded project A Thousand Years of Building with Stone.

The rise of the smartphone: geology by apps

Over the last decade Mike Brooks of BrooksDesign has generated many apps to cover our local geology, including a series along the GeoparkWay and a specific one for Martley (Fig. 8, *overleaf*).

This technology is at the heart of a second recent major project funded to the HWEHT by the Heritage Lottery Fund and local charities (2015–18): 'Voyages in Deep Time' (https://deeptime.voyage/; Harrald 2018). The project's central aim is the development of apps that will enable all, but especially young people, to gain an immersive understanding of geological locations through the use of computer apps (Fig. 9, *overleaf*).

'Voyager' app is a game taking the user on a voyage of discovery and survival in ancient environments and is aimed at young people (ages 10–15 years), but can be fun for everyone. Voyager 'deeptime' is available on the Apple Store and Google Play (search for 'Voyager (by BrooksDesign)'). A second app, called 'GeoExplore', is aimed at 'A' level students or adults with some geological knowledge. It asks them to carry out an investigation at a local geological site and digitally provides the tools needed to do so.

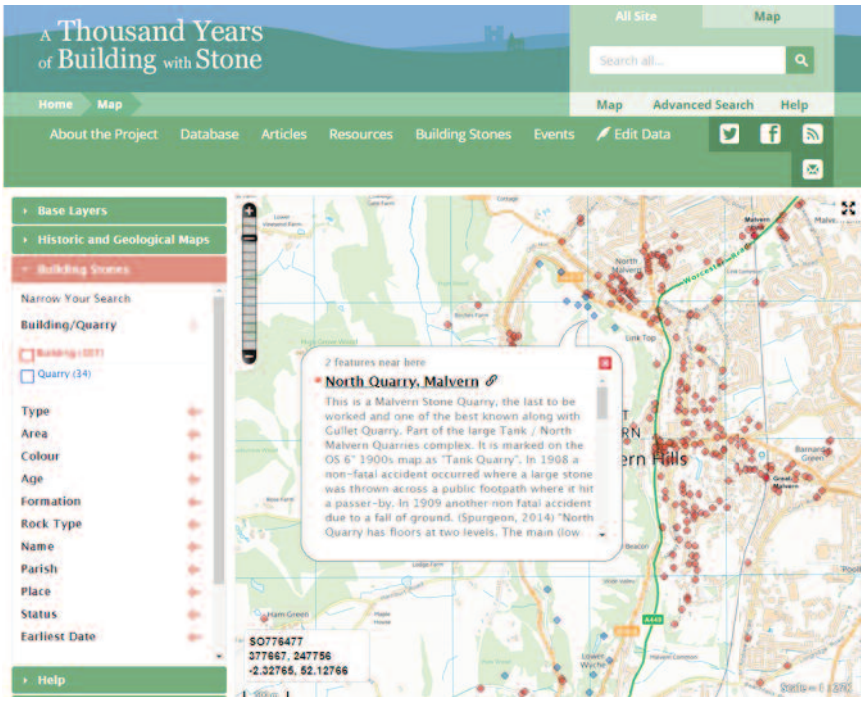

Figure 7 Screenshot of data on North Quarry, Malvern from the spatial database for the project, A Thousand Years of Building with Stone: *http://www.buildingstones.org.uk/ ; further information is obtainable by following the link for the quarry name.*

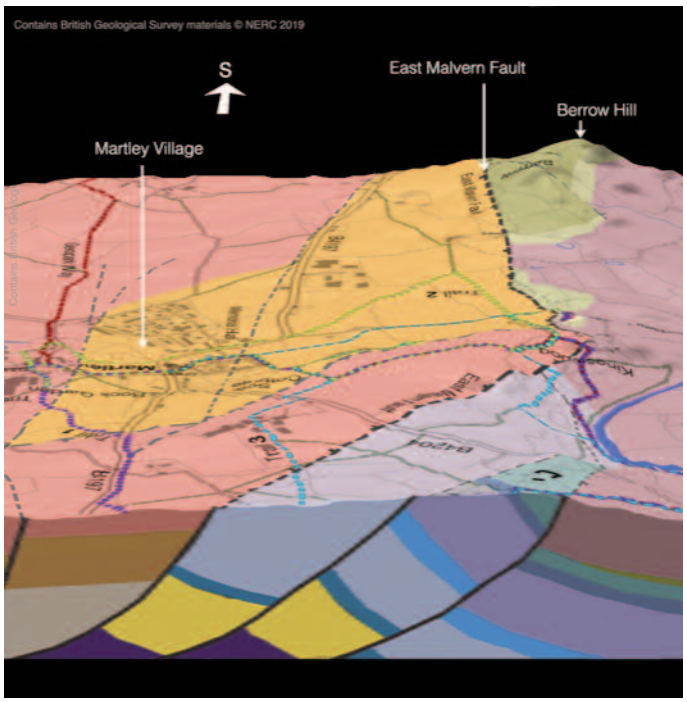

Figure 8 Screenshot from MartleyRocks app by BrooksDesign.

There are four main sites, of which two (Martley and Lickey) are in Worcestershire. Later in 2018, the decision was taken to add some simpler trail guides to classic locations at the Wrens Nest, the Malvern ridge and Bredon Hill.

The Ice Age in Worcestershire

A recent opportunity to synthesize the Quaternary history of Worcestershire (Fig. 10) arose through collaboration with Worcestershire Archaeology and Worcester Museum, which had been funded by the Heritage Lottery Fund to develop exhibitions on the theme of the *Lost Landscapes of Worcestershire* (see https://iceageworcestershire.com/). The exhibitions, which ran through summer 2018, were wide-ranging and imaginative in design. They included classics such as the mammoth tusk recovered from late-glacial gravel workings at Clifton in 2016. A booklet produced jointly by the Earth Heritage Trust and the Worcestershire Archaeology summarises the geological history and archaeological interest, and can be obtained by contacting HWEHT (Anon 2018). One interesting issue is that the descriptions of Quaternary deposits vary greatly between the seven different memoirs and maps of the British Geological Survey. Anglian glaciers (marine isotope stage 12) covered the whole county, but little evidence remains, while the age of tills in the north-east of the county (marine isotope stages 12 and 6) is debated. The main features of international importance are the river terraces of the Severn and Avon (Figs 11, 12 and 13, *opposite*), from which the bulk of the important fossil discoveries have been made and which also evince sustained uplift of the region through the Quaternary period.

A Geo-Garden

The OUGS symposium was held on the University of Worcester's St. Johns campus, where the HWEHT offices are also based. A recent collaboration between HWEHT and the University has resulted in the creation of a Geo-Garden, which showcases spectacular rock samples that are explained via a targeted app that makes use of buried sensors (iBeacons) for precise geolocation. Hence, although Worcestershire has some of England's oldest geology, it also has some of the most up-to-date tools for their study!

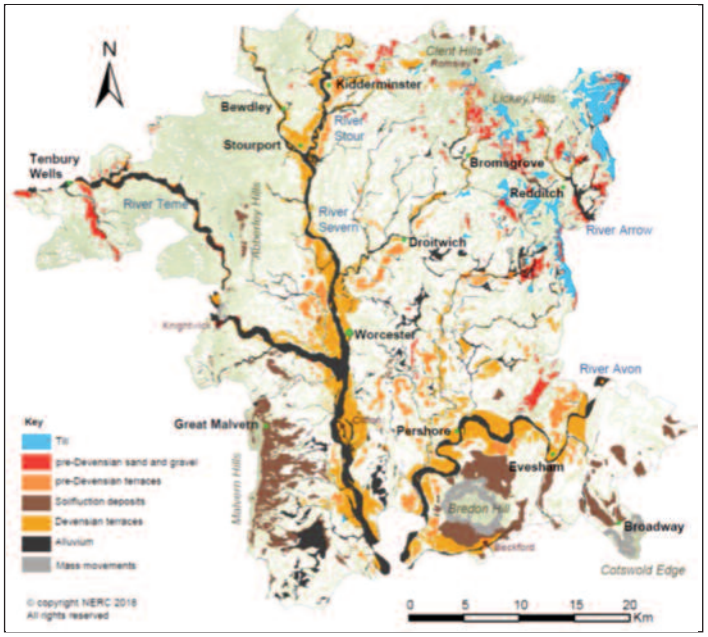

Figure 10 Summary of the Quaternary deposits of Worcestershire from Anon (2018).

Acknowledgements

Thanks to the OUGS for the opportunity to present this material and to colleagues at the EHT for their inputs, not least Mike Brooks in relation to the various apps that are illustrated. Some parts of the text are paraphrased from existing EHT documents.

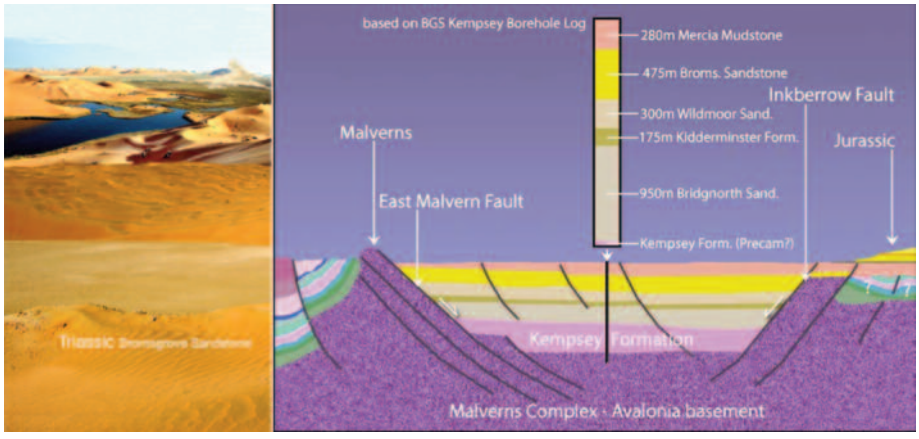

Figure 9 Screenshot of scenes from apps generated in the Heritage Lottery-funded Voyages in Deep Time *project.*

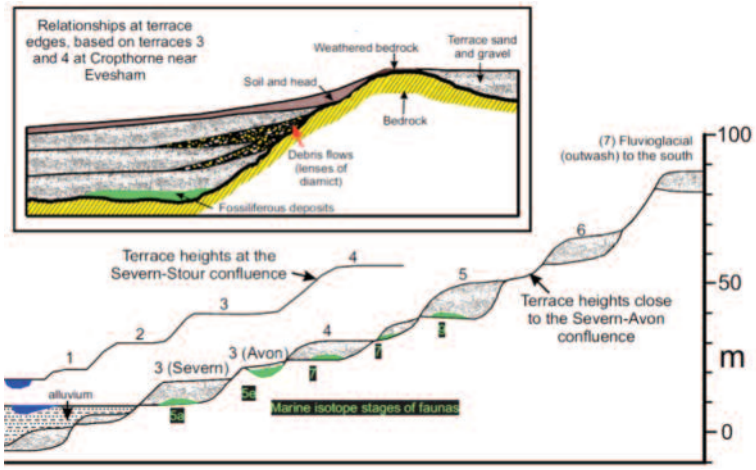

Figure 11 (lower) Quaternary river terraces in Worcestershire (upper) details for some Cropthorne locations (from Anon 2018; redrawn from Maddy et al. *1991 and Penkman* et al. *2013).*

Figure 12 Late Pleistocene river terrace at Clifton, central Severn Valley cut by a Holocene palaeochannel (centre) of the River Severn. (drone photo: Adam Stanford, aerial-cam Ltd/EHT).

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Figure 13 Screenshots of the GeoGarden app by BrooksDesign. The GeoGarden is at the University of Worcester.

Book review

Bjornerud, Marcia 2018 *Timefulness: How Thinking Like a Geologist Can Help Save the World*. Oxford: Princeton University Press (ISBN 978-0-691-18120-2; 208pp; hardback £20.00 [from Amazon], Kindle edn £15.60; other options also available)

I saw this book reviewed in *New Scientist* in November and decided that it looked very interesting so I purchased it through Amazon (it is an American book though published through Princeton's Oxford 'branch'). I have not been disappointed; it is one of the most interesting and informative books I have read for a long time. The book is not large (14.5cm × 22cm) with 'only' 208 pages. It has six chapters, plus a Prologue and Epilogue, three Appendices (or appendixes as is written in the book), an extensive list of references for each chapter and an index. It is written with an American audience in mind (lots of 'home grown' references), but I feel it is appropriate for everyone.

The author, Marcia Bjornerud, is Professor of Geology and Environmental Studies at Lawrence University, Appleton, Wisconsin with particular interests, *inter alia*, in structural geology and earth history. She has written this book to educate the 'interested' public in how knowing the earth's history over the long period since its formation can give us insight into protecting its future sustainability. How we as humans fit into the overall picture over the last 4.5 billion years is at the core: how NOW-ism is not a way forward and how we are but one small blip in history.

At the centre of each chapter is 'time', be it the length of time water stays in the atmosphere or how long various types of rock took to form. Everything is very clearly explained for the layperson, with reference to the relevant Appendix if need be. Footnotes for all references are clearly marked too. There are also hand-drawn diagrams to illustrate some points. She uses good analogies and clearly loves her food, as many of the former are related to the latter! Prof. Bjornerud also uses 'the ages of man' to illustrate how our thinking about time changes as we age, from a child's comprehension of how long a day is (especially a day off school due to snow closures — this is Wisconsin after all), to an elderly person looking back over their life and what they have achieved. Each chapter starts with a relevant quotation from people such as Charles Lyell and Bob Dylan — yes really!

The final chapter is the most philosophical part of a book that also includes many references to much earlier writers, such as Darwin and Freud. Here she looks at what we, as humans, may want to consider to preserve/conserve/protect/save the planet. She is realistic enough to know that, certainly in the USA, a lot of this won't happen either soon or possibly ever! The final paragraph of the Epilogue sums up the message of the book very well and I would like to reproduce it:

"Our Holocene snow day is ending now, and tomorrow's the Anthropocene. We've all enjoyed the fantasy that we can keep playing our self-absorbed and careless games — that when we choose to come inside, our supper will be waiting for us, and nothing will have changed. But no one is home to take care of us. Now we need to grow up and navigate on our own, doing our best with the Atlas of the Past to make up for so much lost time."

— Jane A. Michael, BSc (Hons) (Open)

Book review

Scourse, E. M., Chapman, N. A., Tappin, D. R., and Wallis, S. R. (eds) 2018 *Tsunamis — Geology, Hazards and Risks*. London: Geological Society Special Publication 456 (ISBN 978-1-78620-318-2; 252pp; hardback £90)

The book has a Foreword by the Geological Society of Japan and a Foreword by the Geological Society of London, and comprises 12 chapters: 9 chapters on Tsunami hazards globally and 3 chapters on risk modelling.

I found it irritating that references in brackets were placed in the text and then repeated in blocks at the ends of each chapter. There was also annoying (to me) American spelling.

This is a collection of papers relating to tsunami hazards and risk modelling, mainly referring to Japan, but with chapters on Central America, the Mediterranean region, the UK and New Zealand, with mineral analyses of the various deposits. Informative pictures, tables, graphs, sections and maps are plentiful.

Having some background knowledge of New Zealand, I read that chapter with interest. It describes a model to estimate quantitively the tsunami hazards around the NZ coast, helping evaluate risk and to develop measures to mitigate the hazards.

The areas I know best, Marlborough, Nelson and Canterbury, are particularly vulnerable, with Blenheim, situated on a flat area with hills on either side of the Marlborough Sounds forming a potential funnel from Cook Strait. Similarly, Nelson is at the centre of an extensive bay with flat land behind. Christchurch on the inland side of a volcano — Banks Peninsula — is backed by the extensive Canterbury Plains, stretching back to the Southern Alps.

The cover text states that the book is "aimed at both scientists working in the field and at a wider community interested in tsunami science and natural hazard assessment."

— Rosemary Darby, OUGS, BA (Open), BSc Hons (Open), Teachers' certificates UK and NZ

A brief history of geological time in the building stones of Herefordshire and Worcestershire

Kate Andrew
Herefordshire and Worcestershire Earth Heritage Trust

Introduction

Herefordshire and Worcestershire Earth Heritage Trust (EHT) is a geoconservation charity, first established in 1996 and based in offices on the University of Worcester St John's campus.

Along with Shropshire, Herefordshire and Worcestershire are the most geologically diverse counties in the UK. Herefordshire and Worcestershire have 12 of the 13 recognised geological periods represented in outcrop, with only rocks of Cretaceous age absent (Fig. 1).

The main activity of the Trust is promoting public awareness of this superb Earth Heritage. Running a Geological Records Centre — which involves researching, surveying and designating Local Geological Sites — provides the dataset on important sites and the means to work with planning departments to protect these sites. The Trust also carries out practical site geoconservation.

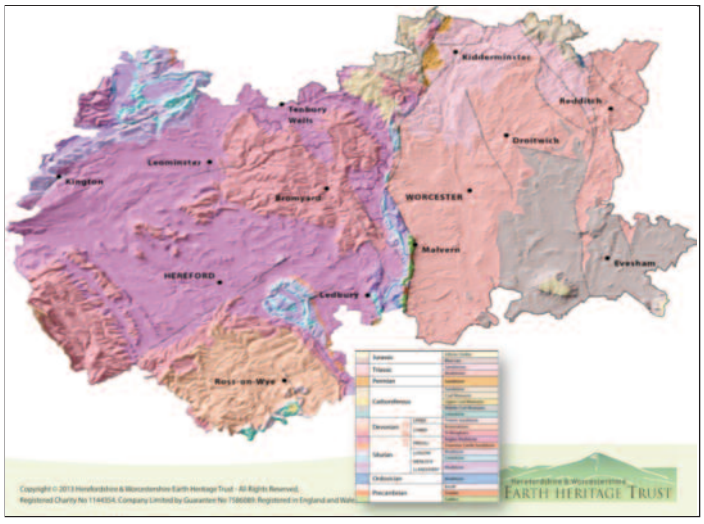

Figure 1 Simplified geological map of Herefordshire and Worcestershire.

'A Thousand Years of Building with Stone Project'

The publication of The Department of Communities and Local Government National Planning Policy Framework in March 2012 recommended that local authorities safeguard important sources of building stone. The lack of understanding of building stone resources and reduction in working quarries led to Historic England (then English Heritage) and the British Geological Survey working together on The Strategic Stone Study to identify, for each county, the significant stone types used in the past, and their potential current sources. Historic England commissioned a series of county Building Stone atlases to record known *building stones* used within counties, representative examples of (listed) *stone buildings and villages* constructed from those stones and known *building stone quarries*.

Atlases for most of England, with the exception of London and East Anglia, were underway or completed by 2017. Work on Herefordshire, Worcestershire and Shropshire was complete in 2011. The atlases can be accessed online via the following link: https://www.bgs.ac.uk/mineralsuk/buildingStones/StrategicStoneStudy/EH_atlases.html

In Herefordshire and Worcestershire, counties known for timber-framed building construction, recording only listed buildings has meant that most of the Strategic Stone Survey records are of churches and higher-status buildings rather than for vernacular buildings. High-status listed buildings are more likely to have been constructed from stone transported some distance at a high cost, rather than from stone sourced from the immediate locality, and therefore are not that representative of local geology.

EHT was aware that the variety of stone types available within Herefordshire and Worcestershire has created many locally distinctive building styles, in particular in vernacular buildings; and that this variety was not widely recognised, and can be highly localised. It was recognised that a more in-depth study would be a good opportunity to work with communities and would widen the understanding of earth heritage and county sources of building stone. A better and wider understanding would also contribute to appreciation and conservation of Herefordshire's and Worcestershire's stone-built heritage and inform planning decisions.

A successful funding application was made to The Heritage Lottery Fund and after a successful project development phase, work started in January 2013 on a £395,000 project planned to run for three and a half years. The project was run by a team of three: a project manager, a community consultant and a technical consultant, with support from the EHT administration and finance team. In the event, the funding available was re-structured and the project was able to run until May 2017.

Heritage outcomes of the project

Since 2013, The Heritage Lottery Fund strategic framework has required funded projects to demonstrate that the funding has made a lasting difference for heritage and people by delivering heritage outcomes.

The key project outcomes were:

1. raised awareness and appreciation of local stone, providing people with a sense of place;
2. re-discovery of local building stone quarries;
3. research on the skills, techniques and people involved in exploiting this resource; and
4. the creation of a useful database linking stone to quarries and to particular buildings.

Cluster concept and volunteer input

The area covered by the project was large, so we aimed to mobilise volunteers to work in 19 specific 'cluster areas' (Fig. 2, *overleaf*). In order to reach new communities and different groups of volunteers, and thus widen the awareness-raising, the cluster areas deliberately avoided the largely aggregate quarries that had been the subject of the previous 'Earth Heritage Champions' project.

EHT has always had good volunteer relationships, but this project is particularly notable for its engagement with volunteers. In total, 191 individuals volunteered on the project, including:

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- 85 volunteers active over a longer period;
- 52 people entered data onto the database;
- and 8,766 hours of volunteer time, equivalent to a value of just under £110,000.

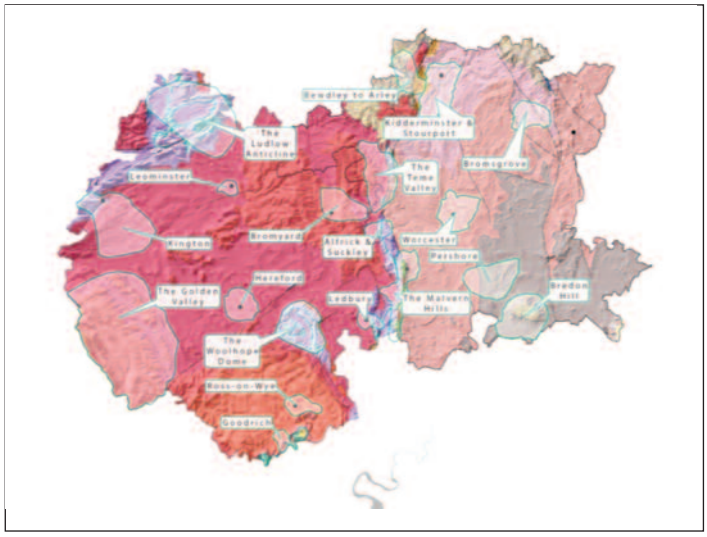


Figure 2 Map of Herefordshire and Worcestershire showing location of 'cluster areas'; 26 possible cluster areas were identified during the development phase. These were refined down to 19, of which 12 lie on ORS (Přídolí or Devonian) rocks.

A useful database and website

After a procurement exercise, a specialist web database was developed for the project by Orangeleaf Systems. This company has extensive experience of developing and hosting platforms that combine searchable local history, archive and museum object content databases with interpretative web pages.

With a personal log-in and following some basic training, volunteers were able to input and upload records of buildings, quarries and the associated research. Most volunteers worked in cluster areas, but some volunteers chose to input specific types of data. For example, one volunteer checked the Worcestershire Pevsner for any mention of a stone-built structure and entered this data, cross-referencing it to any additional data on the Worcestershire Historic Environment Record.

The building stones web database can be located at http://www.buildingstones.org.uk — It holds:

- records of 733 quarry sites
- records of 4,670 stone buildings

Since this was effectively a crowd-sourced project, the data on the site reflects the areas and interests that volunteers were willing to research and record. Data was gathered in all 19 cluster areas, but the most remote from Worcester, the Golden Valley, achieved the least coverage. Owing to a lack of volunteers, little data could be recorded for Pershore and so this cluster concentrated on Croome Court instead. For a few buildings, we were able to get the complete story. The Folly at Gatley Park produced the most complete record: built of Aymestry Limestone from Leinthall Earles Old Quarry, quarried by Mr Gale, a first-hand account from Sir Thomas Dunne of his quarrying technique and a photograph of Sir Thomas and Mr Gale, information that the stone to be used was picked by hand to avoid any pieces with fractures caused by the blasting, designed by architect Raymond Erith, built 1961–64 and extended 1973–76, and even the zone fossil for the Aymestry Limestone, *Conchidium knightii* visible in some of the pieces (Fig. 3).

The website, which will remain live until 2024, contains a lot of supplementary content created to support the volunteers. It also hosts PDF copies of many of the archival sources and publications referenced, together with links to useful sources of data and information.

The database has also been used extensively by Worcestershire County Council for the development of their Minerals Plan, currently in the final stages of consultation before adoption.

Match funding

Thanks to our dedicated volunteers, the match-funding volunteer time target for the Heritage Lottery Fund award was exceeded. With the economic downturn, our cash match funding target of

Figure 3 The Folly at Gatley Park (top) generated the most detailed record; (centre) Mr Gale was the quarryman (seen here with a young Sir Thomas Dunne at the summer fete in the 1960s); (bottom) specimen of Conchidium knightii *(zone fossil for the Aymestry Limestone) in the walls of the Folly.*

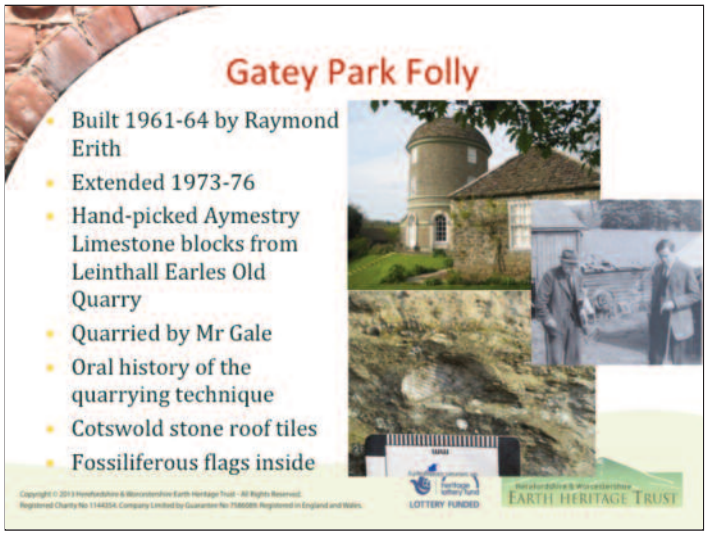

Gatey Park Folly
Built 1961-64 by Raymond Erith
Extended 1973-76
Hand-picked Aymestry Limestone blocks from Leinthall Earles Old Quarry
Quarried by Mr Gale
Oral history of the quarrying technique
Cotswold stone roof tiles
Fossiliferous flags inside
LOTTERY FUNDED
EARTH HERITAGE TRUST

Figure 4 Outreach activities included: (top left) mini-builder activity; (top right and bottom left) Batiks of rocks in thin section and the Bromsgrovia *tetrapod; (bottom right) dry-stone wall building demonstration using stone from Callow Quarry at a country fair in Herefordshire.*

just under £30,000 proved harder to pull together, but was also eventually achieved, thanks to contributions from the Arts Council England, Wye Valley AONB, The Bransford Trust, Malvern Hills AONB, local councillor funds for Worcestershire and Malvern Hills Cllrs Pollock, Hardman, Mallet and Cummings, Forest of Dean Stone Companies, Waitrose Community Fund and income from events, lectures and guided walks.

Outputs

In addition to outcomes we also created a number of quantifiable outputs (Fig. 4, *previous page*):

- nine 'Earth Caches';
- four new building stones trail guides;
- two peer-reviewed papers, in the *Proceedings of the Geologists' Association* and in the *Transactions of the Woolhope Field Naturalists' Club*;
- three contractor roles filled by five individuals over the project (Kate Andrew, Beth Andrews, Elliot Carter, Sue Knox and Ella Young);
- two office support roles filled by five individuals; and
- an extensive event and activity programme reaching 28,929 people (detailed in the table below).

Table of public engagement events and activities delivered

	2013	2014	2015	2016	2017
Talks	3	10	5	4	5
Formal education	1	1	2	1	1
Walks	3	1	6	10	2
Roadshows	3	10	5	2	
Exhibitions		3	5	4	
Conferences		1	2	2	
Stands	5	7	3	6	

Distinctive vernacular building styles linked to uderlying stratigraphy and building stone availability (Fig. 5)

Precambrian

Formed *c.* 700–541 million years ago, the Malvern Hills have a complex history, but are based around metamorphically altered pink granites and black diorites, probably formed at a subduction zone.

The stone is hard and brittle and can vary greatly in colour and mineral content within and between quarries, although lime green epidote and large white baryte crystals are associated with particular quarries. As the extraction process uses explosives, blocks are irregular, can fracture after extraction and are difficult to cut into regularly shaped blocks. The typical building style using the stone is a random stone walling pattern, often with raised strap pointing. The development of this building style is also thought to be linked to the development after 1845, by Isaac Johnson, of the first modern Portland Cement and the establishment of cement-making in Colwall by the canal and railway engineer, Stephen Ballard.

Cambrian

Unlike Shropshire, the Cambrian is not well represented in Herefordshire and Worcestershire, except for the inshore greenish-brown Hollybush Sandstone, formed 541–485 million years ago. There are small outcrops near the southern tip of the Malvern Hills. Extraction is for rubble stone and aggregate at Hollybush Quarry.

The stone was used to build a chapel of ease, All Saints Hollybush, for the quarrying community. Re-pointing of the church in Portland Cement has resulted in serious on-going spalling of the stone surface. On the west elevation and porch, the spalling stone surfaces have been de-frassed and the cement pointing has been replaced with lime pointing, a process that has improved the appearance of the building and should prevent further damage from occurring.

At least one timber-framed cottage in the settlement has a foundation of coursed rubble blocks of Hollybush Sandstone.

Ordovician

Formed 385–445 million years ago, very localised Ordovician outcrops occur in north Worcestershire in the Lickey Hills, consisting of sandstones, quartzites and some igneous material.

The extracted stone was mainly used as aggregate, but it was also said to have been used to build the nearby Frankley Reservoir, part of the Elan Valley water supply for Birmingham (the dam has a stone coping but is largely concrete). It is, however, used in rubble-stone garden walls and other small-scale structures close to the quarries.

Silurian

Formed 443–419 million years ago, the Silurian outcrops on the Woolhope Dome and Ludlow Anticline in Herefordshire, and the Abberley and Suckley Hills in Worcestershire represent lagoon, reef and near-shore deposits. The Wenlock and Ludlow rock types vary from olive mudstones through greenish-grey mudstones to limestones with varying amounts of sand content and muddy partings, making it easy to extract evenly thick pieces. These stone types are usually used as rubble or coursed rubble.

In places, these limestones can be cut into blocks, for example the Wenlock Limestone used in the St Katherine's almshouses at

Figure 5 Rocks from the Precambrian to the Quaternary make very different building styles.

Ledbury and material from Aymestry Great Quarry. Some horizons within the Wenlock and Aymestry limestones have a high organic content and can be polished. Ledbury Marble is a local name for this variety of Wenlock Limestone and was used to make black stone floor tiles (popular in the 18th and early-19th centuries, laid in a chequer-board pattern with white marble). The small cobbles of Church Lane, Ledbury clearly demonstrate the black shine when wet, with the occasional crinoid ossicle present (Fig. 6).

Aymestry Limestone was also used for decorative table-top slabs and for gravestones and monuments such as those of the Knight family at Wormsley. The mud partings in both the Wenlock and Aymestry limestones can make the polished stone liable to fracturing and if used externally, differential weathering that can be quite severe.

The principal building stone of the Přídolí in North Herefordshire and around the Woolhope Dome area is the pale-yellow Downton Castle Sandstone. This is an excellent building stone, with thinly spaced bedding planes. It is often used for lintels and mullions for buildings otherwise using rubble Wenlock or Aymestry limestones, but usually in this situation, it is face-bedded.

Figure 6 Wenlock Limestone cobble with crinoid ossicles and other fossil shell debris —view of Church Lane Ledbury, paved in Wenlock Limestone cobbles.

Devonian

These deposits are dated 419–358 million years ago and are known collectively as the Old Red Sandstone (ORS). These rocks formed at a time when Britain was near the Equator with arid desert conditions and occasional dramatic flash floods. Most of Herefordshire and some areas of west Worcestershire have ORS deposits, mapped as Brownstones and St Maughan's Formation. However, these rocks are far from uniform: they are not all sandstones and not all red, and different deposits can have very distinctive colour and grain size variations, even within a single block of stone.

In the project, we explored the ORS of the Bromyard area in detail, and published a paper on it in the *Proceedings of the Geologists' Association* (Andrew *et al.* 2017). We also used a hand-held portable X-ray Fluorescence (XRF) machine to explore the correlations between colour and appearance of ORS rock types used in Bromyard buildings and a number of local quarries, looking at the distribution of K, Al, Zn and Mn plotted against Fe/Ti, which started to show distributions suggesting links between the local variations in stone types and specific quarry sites (Andrew *et al.* 2017).

Several distinct units are present and can be mapped in the Raglan Mudstone *(e.g. see Fig. 12, page 18*). The Bishop's Frome Limestone (previously known as the Psammosteus Limestone) is one of several 'cornstone' horizons — a limestone formed by precipitation of calcite at the water table within a soil horizon in very arid conditions. The Hay Sandstone, a pale-grey, fine-grained sandstone, is used extensively for building in Hay on Wye. A unit with very large, rounded, white quartz pebbles, was extracted for making cider millstones.

Work on medieval churches in Herefordshire and Worcestershire indicated a preference for selecting pale-grey to white cross-bedded sandstone for the towers, often with quartz pebbles and in very large, squared blocks, but often of random sizes. Similarly, at Goodrich Castle the keep is built from a pale whitish-grey sandstone with angular quartz pebbles, distinct from the red sandstone used on the bailey walls and corner bastions. Presumably the tall pale-coloured stone towers really stood out in the medieval landscape, indicating power and status and providing navigational aids (Fig. 7).

Figure 7 Pale-coloured, often cross-bedded sandstones with quartz pebbles of varying size were used for medieval towers in churches across Herefordshire and Worcestershire, and in the keep of Goodrich Castle (bottom right).

Carboniferous

Formed 358–298 million years ago, a rise in sea level left much of Britain under a shallow sea. Deltas formed from the high ground, creating thick sandstone bands, often containing fossilised plant material. Stanley Quarry at Highley, just into Shropshire, was a significant ecclesiastical medieval quarry yielding a buff to pale-grey, calcite-cemented sandstone that could be extracted in blocks using the wedge and groove method. Most churches downstream of this site, within easy reach of the rivers Severn and Avon, contain stone from this quarry, recognisable by its characteristic ironstone concretion nodules.

The Pennant Sandstone from the Forest of Dean provides a good colour match, and has sometimes been used for repairs, but since the sand grains are cemented with silica rather than with calcite, it is much harder and repairs are likely to exacerbate differential weathering.

Permian

These rocks, formed 298–252 million years ago, are exposed along the Severn Valley near Bewdley. The station yard at Bewdley station is formed from a quarry that extracted the stone for use along the railway line, including the Wribbenhall viaduct in Bewdley. The red sandstone formed from fossilised sand dunes created in hot dry desert conditions. The cement re-pointing patching in engineering brick dates from an upgrading of the line during the First World War.

Triassic

Triassic rocks formed 252–201 million years ago are found across much of Worcestershire. During the Triassic Period the environment slowly changed from a flat, arid environment with large rivers and evaporating salt lakes to a marine environment. A mixture of sandstones, conglomerates and mudstones formed. Colours vary from red to grey and pale green. Stone from the quarry at Hadley was used to repair Worcester Cathedral in the 1890s. Building stone and stone for water troughs was also quarried around Ombersley, Droitwich and, once a rail link was in place, from Bromsgrove.

Jurassic

Jurassic rocks are found in south-eastern Worcestershire, and formed 201–145 million years ago. During the Jurassic the area was under tropical seas; in deeper water these conditions formed carbonate mud, often full of fossils. As sea level dropped, oolitic limestone formed in tidal lagoons, similar to those in the Bahamas today. The distinctive Cotswold Limestone is oolitic. The Lias flags are typical of the deeper-water carbonate mud.

Quaternary

Formed from 2.5 million years ago to the present, these are the youngest rock formations used in buildings in the two counties. The most common is tufa, formed at spring lines, where water has percolated through lime-rich horizons and precipitated, often onto moss and other plants. Photosynthesis by the plants causes a change in pH, and causes precipitation onto the substrate, this creates the stone's distinctive void-filled texture. (Harding 1998). Tufa is easy to cut and can be sawn into blocks when fresh, but becomes very hard, yet lightweight, when dry. Owing to the method of deposition, it is usually only formed in small, localised patches.

Tufa was employed as the lightweight vaulting infill in the south aisle of Worcester Cathedral (the medieval equivalent to breeze blocks). It is used for entire church buildings, such as St Andrew's Church, Shelsley Walsh. Southstone Rock, an exposure of tufa *c.* 30m high, was a major source for St Andrew's tufa, with its decorative striped bands, but also just as occasional blocks in other churches. The location of isolated tufa blocks on the corners of churches otherwise built of difficult-to-carve ORS hints that the builders deliberately put tufa blocks in the corners to provide places to carve consecration crosses. Ewyas Harold Church in Herefordshire has good examples on the south wall of the chancel (Fig. 8).

Though not strictly a building stone, the River Severn terraces provide well-graded, rounded paving cobbles used around the north porch at Worcester Cathedral. The causal disbursement record for works by Capability Brown at Croome Court between 1750 and 1757 record payments for more than 130 tonnes of pebbles extracted from Defford and Severne Stoke. These River Severn terrace pebbles were presumably used to surface paths, including the cobbles under the dry bridge.

Figure 8 Tufa blocks (showing as slightly pink, circled in red) in the chancel wall of Ewyas Harold Parish Church.

1,000 years of building with stone

Stone has been used as a building material in Herefordshire and Worcestershire for at least 1,000 years. However, at the time the EHT project commenced, there were only two active building-stone quarries and a few delves in Herefordshire and none in Worcestershire. In total, the project identified 733 'forgotten' quarries.

A number of examples of Anglo-Saxon stone buildings survive in the two counties. Herringbone construction, a technique to build effectively with even thicknesses of rubbly stone, can be seen at Edwyn Loach Old Church and at Wigmore Parish Church. Long and short block work at the corners of rubble-constructed buildings is a typical later Anglo-Saxon technique, seen for example at Kilpeck Parish Church (Fig. 9). Parts of Worcester Cathedral are also Anglo-Saxon in age.

Figure 9 Kilpeck Church, Herefordshire with long-and-short Anglo-Saxon work; Anglo-Saxon herringbone walls at Edvin Loach Old Church, Herefordshire; and the Gatley Park estate office, a stone building dating from 2012.

The most recent stone building surveyed during the project, the Gatley Park estate office, dated from 2012, although built from coursed rubble Aymestry Limestone, more usually used for aggregate.

Re-discovering local building stone quarries

With only two active quarries and a few delves known in Herefordshire and no active stone extraction in Worcestershire when the project began, there were plenty of older quarries waiting to be re-discovered. In all, the project recorded 733 quarries that had been in use from the Middle Ages to the 20th century, most of which lie within the two counties. Although we were aware of archival records of stone from Stanley Quarry, just over the border into Shropshire, being used in the medieval construction of Worcester Cathedral, the oldest evidence of quarrying uncovered were the medieval wedge pits in the dry moat at Goodrich Castle (Stanier 2000). After scraping away at the moss on site, we were able to re-identify the feint triangular marks illustrated in Stanier's photograph.

Some quarries, such as those on the Silurian of the Gatley Estate were so weathered following the end of extraction that they had the appearance of natural valley features. As the project proceeded, we became adept at spotting the evidence of even tiny sections of vertical rock faces in undergrowth or infilled depressions that can only have been the result of human stone extraction activity.

In areas with stone boundary and garden walls, the supply of stone must have been extensive and close by. This is demonstrated clearly at Quarrelly Quarry near Longtown, Herefordshire. The thinly bedded sandstone horizons yielded large slabs used to make the vertical stone stiles characteristic of this part of Herefordshire; large sheets of stone were also used like corrugated iron on barn walls; and the waste stone was used to build drystone walls up to *c.* 50m from the quarry, but any farther away, boundaries reverted to hedgerow.

We were aware that the Lias flagstone quarries around Street in Somerset had migrated across the landscape as the resource was exploited. The quarrying technique on the shallow-dipping beds was to back-fill the exploited area with waste stone and cover this with the overburden before re-planting with orchards, and thus

Figure 11 Lidar image showing a small quarry with feint circular swirls to the right suggestive of back filling and an image of the same area from Google earth with a working face just visible under scrub (Produced by the Environment Agency and used with Open Government Licence).

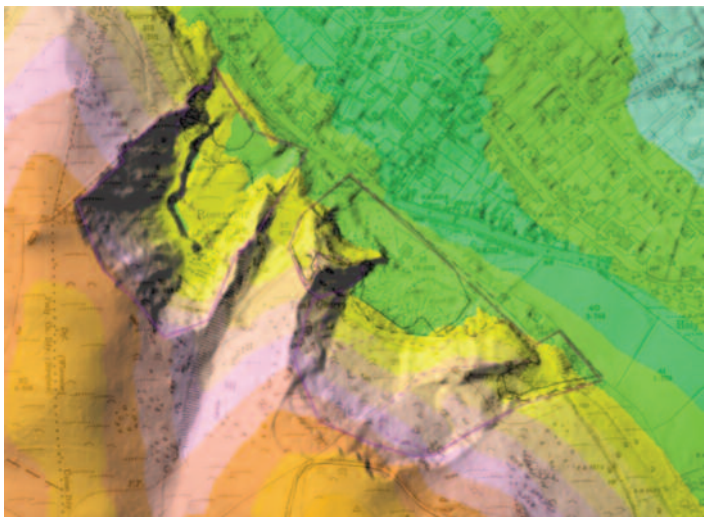
Figure 10 Brick-like blocks of Blue Lias siltstone in the wall of Fort Royal Park.

move the working face forwards. The Worcestershire Blue Lias horizons were exploited for flagstones, but the even thicknesses of the beds also creates useful brick-like Lias stone blocks, as seen in the railway viaduct in Worcester, the walls of Astwood cemetery, Fort Royal park on the London Road and Pitmaston House in St John's (Fig. 10).

However, we were unable to locate any mapped Lias quarries, as extraction must have ceased well before the first edition of Ordnance Survey was published in 1885. This was the case even around the Littletons, where the estate boundary wall is in places 2.5m high and most gardens have stone walls, too, indicative of a nearby stone source. Where back-filling had not been completely comprehensive, Lidar images were used to spot indentations in the ground and feint marks of back-filling that could then be confirmed by aerial photography as the remains of small quarries (Fig. 11).

We also used Lidar and map regressions to map the change of quarrying at Malvern from local aggregate and building to the huge scale extraction in the later 20th century (Fig. 12).

Figure 12 Lidar image over OS map showing the growth of Tank Quarry over time: up until WWI stone was moved by steam lorry; after WWI by diesel lorry; by the 1970s large scale aggregate extraction for motorway building was underway (1880 = solid black line, 1900 = dashed black, 1920 = dashed purple, 1970 = solid purple) (Produced by the Environment Agency and used with Open Government Licence).



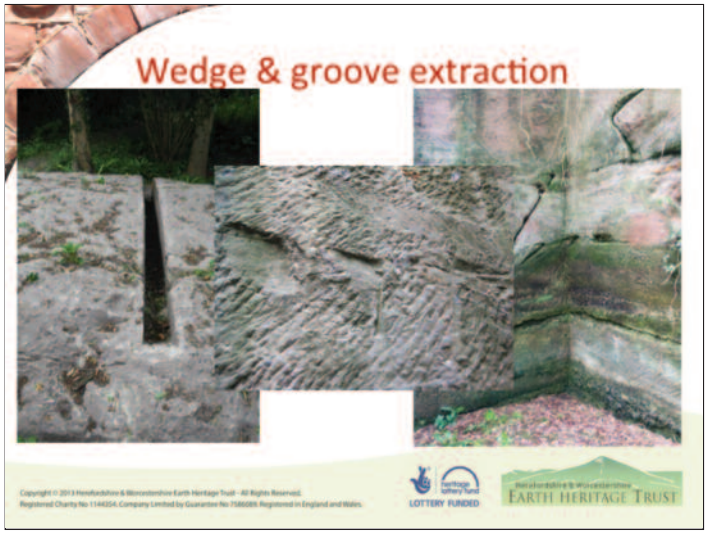


Figure 13 (left) An unused extraction groove, cut by hand with a pick-axe at Hadley Quarry, Worcestershire; (centre) herringbone effect created by pickaxes making extraction grooves, and wedges where the blocks have been lifted by crowbars — seen on the faces of Stanley Quarry, Shropshire; (right) the abandoned faces of Hadley Quarry, Worcestershire.

Researching the skills, techniques and people involved in exploiting the resource

To understand modern extraction and processing techniques, we undertook a number of visits to active quarries in the Forest of Dean, using a modernised plug and feather extraction method and to Callow Hill Quarry (operated by Black Mountain Quarries) in Herefordshire. We also visited Hadley Quarry near Ombersley, Stanley Quarry in Shropshire (source of stone for many medieval churches in the Diocese of Worcester) and the quarry sites at Caplar, where stone used for repairs to Hereford Cathedral in the 18th and 19th centuries was quarried (Fig. 13).

At Hadley Quarry, the Triassic sandstone was extracted until the 1890s using the wedge and groove technique. A groove was picked out by hand and the blocks levered off with crowbars along the partings between the cross-bedded units, resulting in the characteristic herringbone pick marks, extracted blocks were moved via the tiny Hadley Brook onto the River Salwarpe and then onto the River Severn. The existence of a half-timbered weigh bridge still operational in 1955 in nearby Ombersley suggests that the quarries that follow the line now taken by the A449 Ombersley bypass did move stone by road in the 20th century.

At Caplar, next to the metalled track that leads down to a wharf on the river Wye, a large block of stone awaiting transportation by river is still chocked up on small piles of waste stone. Close to Hexton's Quarry between Highley and Upper Arley on the bank of the River Severn, a big pile of dressed oblong blocks of stone are still stacked next to the river (Fig. 14).

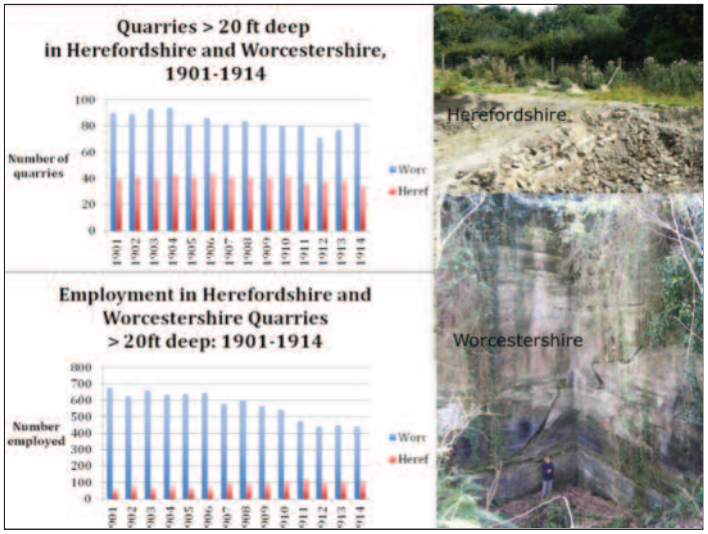
Stone is heavy stuff, and until the advent of steam and then of diesel lorries at the start of the 20th century, could only be moved a few miles by packhorse, horse or ox cart. It was therefore reliant on transport in the two counties by the rivers Wye and Severn and their navigable tributaries, by a few canals from the late 18th and early 19th centuries and by rail only after the 1850s.

Although obvious in retrospect, until we became more familiar with building stone extraction methods, it took some time to realise that tall flat quarry faces with neat 90˚ angles in the corners are indicative of sites worked for dimensional stone. These will normally have been worked by wedge and groove, or by plug and feather techniques. Stone used as coursed rubble or random walling does not need to be extracted so neatly and so can be extracted by blasting, or simply by digging, and will result in much more uneven quarry faces.

Research by a project volunteer Anne Spurgeon on the annual reports from 1901 to 1914 of the Mines and Quarries Inspectorate revealed huge variation in patterns of quarrying between Herefordshire and Worcestershire, with apparently far more quarries and far more quarry workers in Worcestershire than in Herefordshire. However, only quarries more than 20ft (6.1m) deep were covered by the Act and our own data recorded almost three times as many quarries in Herefordshire than in Worcestershire (Fig. 15). This is because the nature of the stratigraphy meant that quarrying in Herefordshire was mostly extracting

Figure 14 (left) A large quarried block chocked up on waste stone sits next to the metalled track through Caplar Woods, still waiting to be moved down to a small wharf on the River Wye; (right) dressed blocks from Hexton's Quarry stacked next to the River Severn.

Figure 15 Graphs of numbers of quarries greater than 20ft (6.1m) deep in Herefordshire and Worcestershire 1901–14; and of the numbers of quarry workers in such quarries during 1901–14.



thinly bedded ORS horizons limestones from shallow delve-type extractions, where stone extraction was an autumn and winter activity undertaken by labourers who would be working on the land during the spring and summer. Because of this working pattern, they were normally recorded as labourers rather than as quarry workers on census returns. A study of *The Builder Magazine* showed that extraction of new stone in the two counties halted during the First World War and never really re-started afterwards (Fig. 16).

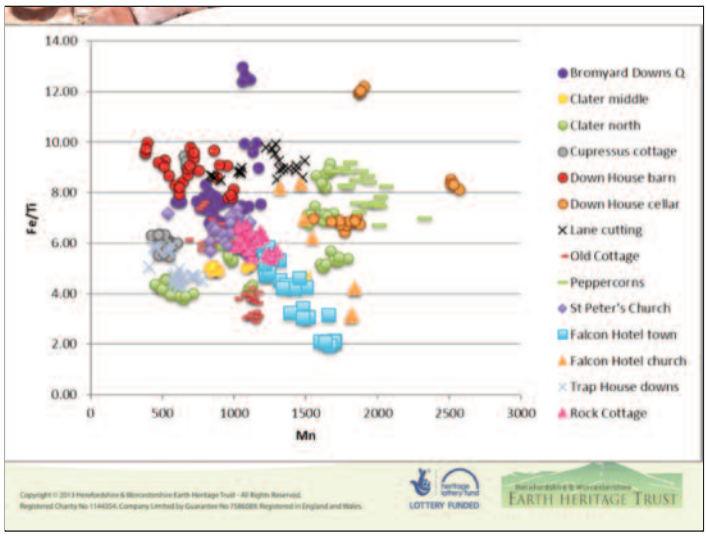


Figure 16 XRF data from a number of quarries and buildings in the Bromyard area, showing clear trends and suggesting that quarry source and building could be linked.

This research also located a report in the *Worcestershire Advertiser* of an accident in 1906 in the Malvern quarries that led to the death of quarry worker, George Phillpotts. This provided a rare window into the life of a named individual and the blasting and face clearing-down techniques used in these quarries. Later in the project, we uncovered more of the story of quarry workers migrating from the Cradley sandstone quarries to the developing Malvern stone quarries. George Philpotts' family stayed living in Cradley, but following his death, the family was left in poverty and reliant on a weekly loaf of church charity bread and a payment of two shillings a week from the Oddfellows Friendly Society, membership of which his employer had arranged (http://www.buildingstones.org.uk/the-human-cost-of-getting-stone/ ; Hunt 2002).

Researching named individuals and the techniques they employed to work stone proved very difficult until a contact made through the Welsh Stone Forum resulted in a regular exchange of information with Michael Statham. Through Michael's work on the archives of the family firm of Clarke's of Llandaff, we were given access to digital copies of the day books, bill books and senior partner's notebook associated with any projects the firm had undertaken in Herefordshire. This included the creation of a reredos and the altar at Hereford Cathedral. After transcription and considerable more research, we were able to piece together the detail of the time spent, rates of pay for different levels of skill, the named masons and their backgrounds, the source of stone, the artist, the client and the life story of the dedicatee, Basil Webb and his 247 comrades, wounded or killed in action on 1 December 1917. This has been recently published in the *Transactions of the Woolhope Field Naturalists' Club* (Andrew 2017).

Conclusion

The *Thousand Years of Building with Stone Project* was highly successful in engaging large numbers of volunteers and in delivering the outcomes agreed with the Heritage Lottery Fund. It created a dataset of information in some depth for the selected cluster areas and more broad-brush information for elsewhere across the two counties, and provided a much better understanding of local variations in building stone within the two counties. The dataset has been employed by Worcestershire County Council is developing their new Minerals Strategy. The project website and database will remain accessible for a number of years and the data have also been migrated onto the two county Historic Environment Records.

We would like to see other areas of the country using the database, but this would require some funding to undertake the necessary revision of the coding to add the necessary term lists.

We have used hand-held XRF successfully to get sufficient data to match a series of glacial erratics in Cotteridge Park, Bournville to those listed in the original published paper after many years of relocations within the park (http://www.birminghamconservationtrust.org/2018/07/13/friday-photo-cotteridge-glacial-boulders/). We hope to undertake further work using hand-held XRF to determine whether stone extracted near by, during a civil engineering project *(as seen in Fig. 12)*, is a match to the sandstone used for the construction of a medieval monastery building and to work with a mason to determine if it could be used for repairs.

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Martley Rock, Worcestershire — a Victorian gem unearthed

William J. Barclay, Susan Hay and John Payne

WJB — formerly of the British Geological Survey
SH — Herefordshire and Worcestershire Earth Heritage Trust
JP — Herefordshire and Worcestershire Earth Heritage Trust

[Editor's note: Dr Susan Hay and William Barclay delivered successive lectures at the OUGS 2018 Symposium, describing aspects of Martley Rock's importance in geological research, and the work of the Herefordshire and Worcestershire Earth Heritage Trust, the Woolhope Naturalists' Field Club, the British Geological Survey (BGS) and the Teme Valley Geological Society. Here they have written a joint article on this material with their colleague Dr John Payne.]

Abstract

A small Victorian gravel pit 1km west of the Worcestershire village of Martley has had an influence over the past 200 years that far outweighs its size or economic importance. It exposed part of an inlier of Precambrian and Lower Palaeozoic rock, when first recorded by Roderick Murchison in 1839. Many eminent geologists followed him through the 19th and 20th centuries, comparing and contrasting it with the exposures in the Malvern Hills to the south. The pit was backfilled and planted with conifers in the late 1980s.

A chance meeting between a geologist and the pit site's owner in 2004 reignited interest and led to a programme of trenching across the pit and the neighbouring land. The trenching has revealed a complex structure attributed to Variscan compressive forces concentrated on the East Malvern Fault (EMF). The inlier, comprising rocks ranging in age from Late Precambrian (Neoproterozoic) to Carboniferous, lies in the western footwall of the EMF. This major, long-lived lineament in the Midland Platform was subsequently reactivated during Permo-Triassic extension, forming the western boundary of the Worcester Graben. Structures described previously in the disused pit at the site lie within a fault zone named the Martley Rock Fault. The rocks of the inlier are disposed in a series of stacked thrust sheets, the thrusts being interpreted as footwall shortcuts to the EMF.

This study at Martley Rock has resulted in improved accuracy of the geological map of the inlier and an increased understanding of its structure, and has provided new petrographic data on the rocks. In addition, the study, involving amateur and professional geologists, has generated a growing interest in rocks and landscape locally. It has also been seminal in the establishment of a new local geological society and of Martley's 'European Geo-Village status'.

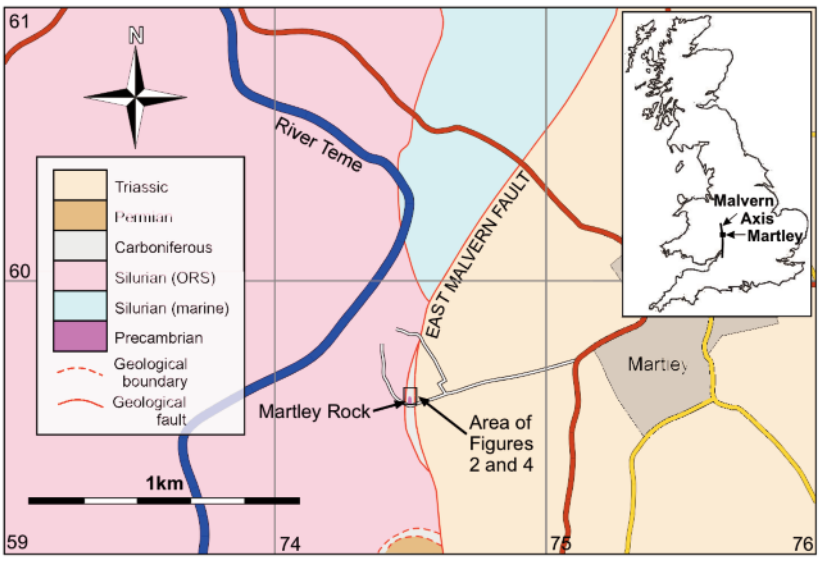
History of research

Roderick Impey Murchison was the first geologist to visit the site. In the *Silurian System* (Murchison 1839), he described a little boss of syenite, intruded into the Old Red Sandstone, that had been recently cut into. He was followed by Victorian geologists such as Phillips (1848), Symonds (1872), Coles (1898), Callaway (1898) and Groom (1898, 1900). Groom's (1900) account remained the definitive description of the site. The early authors described the exposures in the pit as rotten or decomposed syenitic rock and correlated it with the igneous rocks of the Malvern Hills to the south. Later visitors such as Coles (1898) mentioned the presence of a quartzite (quartz arenite), but were divided as to its regional correlation. Coles suggested that the pit did not seem to have been recently worked and thought it likely that the workings seen by Phillips (1848) had been back-filled and the present one had been worked to greater depth, probably on the discovery of the quartzite. More details of this period of historical research are given by Barclay *et al.* (2012).

The area of the site (Fig. 1) was mapped at 1:10,560 scale by the Geological Survey in 1937 (Mitchell *et al.* 1962). It was remapped at 1:10,000 scale by the British Geological Survey in 1985 (Barclay and Rathbone, 1990). In the course of this survey, one of us (WJB) was one of the last people to see what remained of the pit in the 1980s. The pit was then completely infilled and planted with conifers by the South African rugby player Ruben Kruger while working on the farm and playing for Worcester. He is probably better known as a member of the South African team that won the Rugby World Cup in South Africa in 1995.

With the pit infilled, research at Martley Rock stopped until 2004, when Dr Paul Olver visited the site and met the owner. The following year he returned, leading a field trip for the Geology Section of the Woolhope Naturalists' Field Club. Two of us (SH & JP) were among this group. Although there were no *in situ* rocks visible at the site, it was very noticeable that there was very poor crop growth in the field immediately to the north of the pit, with igneous rock fragments on the surface and only a few centimetres of soil on top of the bedrock. In early 2010 Paul was invited by Helen and Richard Turner, the owners, to visit the site

Figure 1 Location of the Martley inlier and generalised bedrock geology (Geological Map Data BGS © UKRI 2019; © Crown copyright and database rights 2019 Ordnance Survey (100025252)).



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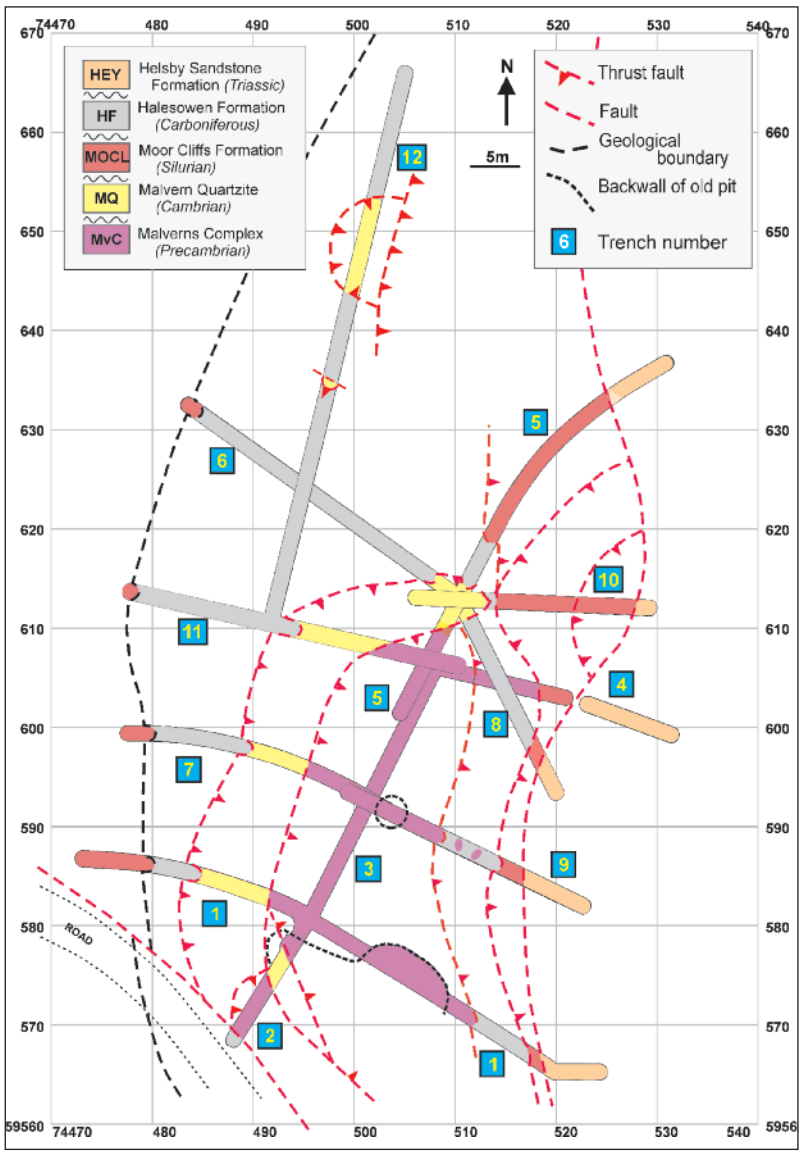


Figure 2 Plan showing the trenches and their geology.

to discuss the possibility of exposing the rock by digging a trench. On arrival Paul found a tractor with bulldozer attachment waiting for him to show where the first trench should be opened. Two trenches were dug that day, the first around the northern edge of the old pit (Trench 1) and the second at right angles across the western edge of the pit (Trench 2) (Fig. 2).

The excavation of these trenches resulted in raised interest in local geology and a series of evening classes were held, leading to the formation of the Teme Valley Geological Society *(Cropp, this volume p29)*. In 2011 the local community secured European (LEADER) funds aimed at making the geology of the parish better known and more accessible. This grant provided funding to enable the opening of a further ten temporary trenches and several pits from 2011 to 2014 (Fig. 3). The research was a combined effort by professional geologists and amateurs from the Woolhope Naturalists' Field Club, the Herefordshire and Worcestershire Earth Heritage Trust and the Teme Valley Geology Society, led by one of us (WJB of the British Geological Survey).

Geology

The geology of the site, as previously recorded by Mitchell *et al.* (1962) and mapped most recently in 1985 (British Geological Survey 1990), comprises rocks ranging in age from Late Precambrian (Neoproterozoic) (the Malverns Complex) to Triassic (the Helsby Sandstone Formation) and includes the Early Cambrian Malvern Quartzite Formation, the Late Silurian Moor Cliffs Formation, and the Late Carboniferous Halesowen Formation. The trenching work done in this study has improved greatly the accuracy of the geological mapping of the lithostratigraphic units present (Fig. 4, *opposite above left)*. Central to the site is a small inlier of meta-igneous rocks of the Malverns Complex forming a topographic mound covered by gravelly soil of weathered igneous rock, into which the former pit was excavated. The inlier lies within metres of the East Malvern Fault, with the Helsby Sandstone Formation in close proximity to the east in the hanging wall of the fault. Surrounding the inlier on the western footwall side of the fault is a thin drape of mudstones of the Halesowen Formation. This rests unconformably on red mudrocks of the Old Red Sandstone-facies Moor Cliffs Formation on the west side of the inlier. Similar red mudrocks occur in a complex thrust-faulted relationship with the Halesowen Formation on the east side of the inlier, adjacent to the East Malvern Fault.

Stratigraphy

Precambrian (Neoproterozoic) — Malverns Complex

The meta-igneous rocks of the inlier (Fig. 5, *opposite below left*) have been variously described as rotten or badly altered syenite, diorite and by various metamorphic terms. Early authors (e.g. Murchison 1839; Phillips 1848; Coles 1898; Callaway 1898; Groom 1898, 1900; Mitchell *et al.* 1962; Phipps and Reeve 1969) correlated these rocks with those of the Malvern Hills. However, few provided rock names or detailed mineralogy, making comparison with closely constrained modern rock types difficult. The rocks previously described were all taken from within the former pit. This study gives the first description of a relatively unaltered hornblende-bearing diorite, providing better comparison with the diorites found in the Malvern Hills.

Coles (1898) was the first to give a detailed description of the mineralogy of a rock from Martley, comprising chloritised green mica including biotite, large fractured kaolinised feldspars and very little quartz. He termed the rock a quartziferous mica-syenite or possibly a diorite. Phemister (in Mitchell *et al.* 1962) described two samples as a crushed granite and an altered gabbro.

Figure 3 Photograph of 2014 trenching. View looking SSW. Trench 1 lies along the edge of the trees (photo: John Nicklin).

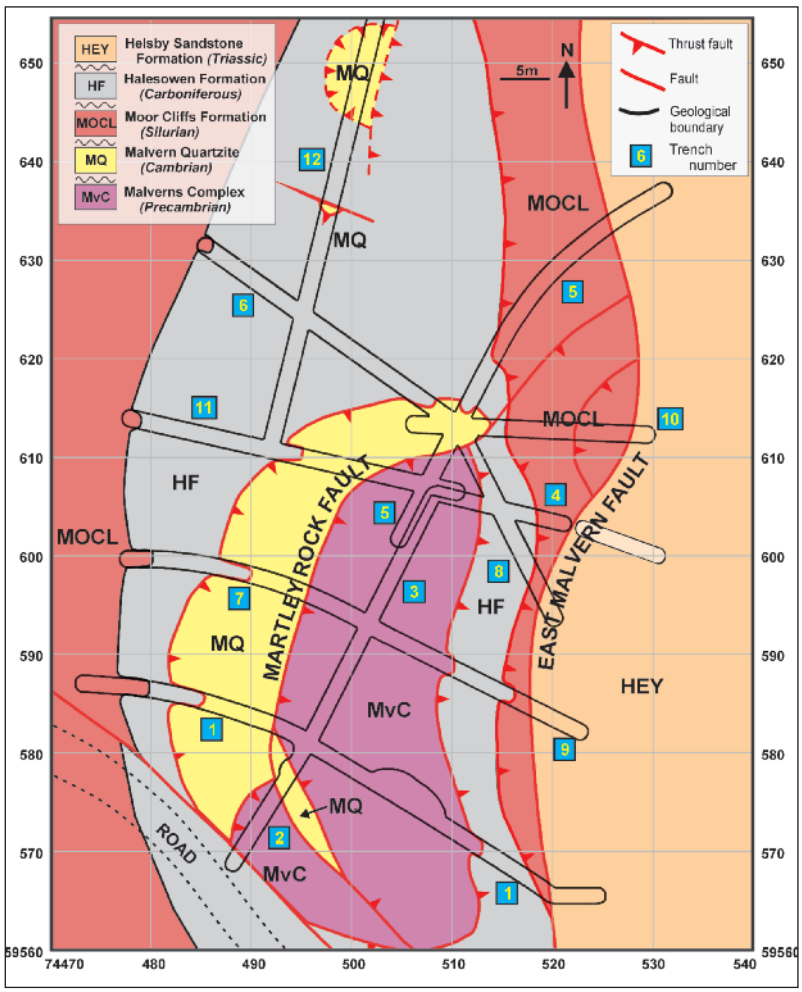


Figure 4 Geological map of the Martley inlier.

Lambert and Holland (1971) noted that diorite and tonalite form 70% of the outcrops in the Malvern Hills and reported diorites from Tank Quarry at the north end of the hills composed of andesine, hornblende and biotite. Strachan *et al.* (1996) described several hornblende diorites and meta-diorites from the northern part of the Malverns, but only one sample contained biotite.

All later workers have also correlated the meta-igneous rocks of the inlier with the Malverns Complex of the Malvern Hills (Pharaoh and Gibbons 1994). These have an igneous crystallisation date of 677Ma, with subsequent thermal reactivation at *c.* 610–600Ma and metamorphic recrystallization at *c.* 550Ma (Strachan *et al.* 1996; Barclay *et al.* 1997). The rocks of the Malverns Complex in the Malverns show abundant evidence of hybridisation, metasomatism and metamorphism, in addition to the shearing, which imparts a gneissose fabric to some of them (Barclay and Pharoah 2000). The Martley rocks are little different.

Variations in the meta-igneous rocks exposed in Trench 3 led to sampling at 3m intervals along the 18m of exposure. The samples become fresher away from the old pit, with crystal size increasing to a maximum at about 15m along the trench before decreasing slightly. For these reasons, a sample from 15m (MR13) was selected for detailed study. MR13 is a grey-pink, medium-grained diorite (Le Maitre *et al.* 2014) comprising andesine plagioclase (54%; average An_{45}), amphibole (18%), biotite (14%), and minor quartz, oxides, zircon and apatite (Fig. 6). The subhedral plagioclases are fractured with corroded ends and have been variably altered to sericite. The euhedral amphiboles are extensively chloritised, forming clots with the partially chloritised biotite and the oxides.

In addition to the mafic varieties, altered felsic meta-igneous rocks samples also examined are marked by their lack of alkali feldspar, suggestive of a tonalitic composition. Together with the diorites they appear to form the majority of the Precambrian rocks at Martley. Felsic quartz-feldspar pegmatitic rocks also occur to a minor extent. All the lithologies show a high degree of shearing.

Figure 5 Jointed meta-igneous rocks of the Malverns Complex in a widened embayment around the backwall of the former pit, Trench 1.

Cambrian — Malvern Quartzite Formation

The very tough, fine-grained, highly sheared quartz arenite of the inlier has been correlated both with the Lickey Quartzite of the Lickey Hills (Coles 1898) and with the Malvern Quartzite Formation of the Malverns (Groom 1898, 1900). The Lickey Quartzite has been shown by Molyneux (in Old *et al.* 1991) to be of Ordovician (Tremadoc or Arenig Series) age and the Malvern Quartzite is Cambrian (Comley Series) in age. The work at Martley has made possible the first description of fresh quartz arenite and collection of a sample for palynology.

Figure 6 Photomicrograph of a diorite from the Malverns Complex. Sample MR13: A = amphibole, B = biotite. The rest of the image is composed of altered plagioclase and largely cubic iron oxides.

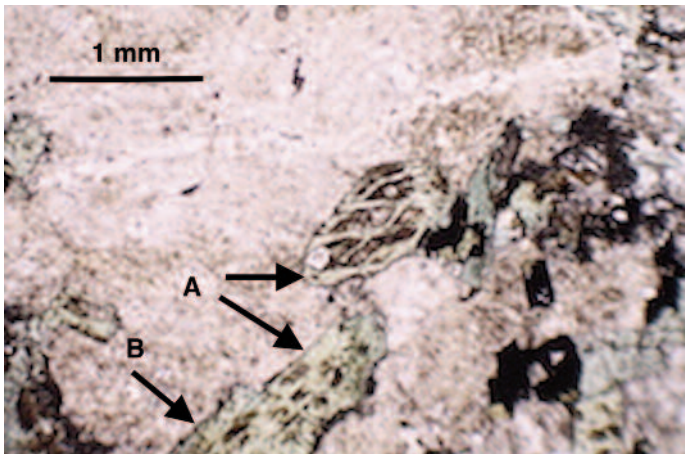


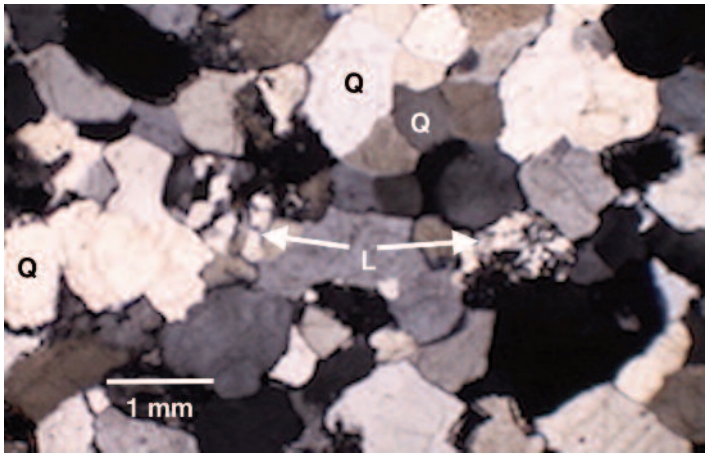
Figure 7 Tectonised quartz arenite of the Malvern Quartzite Formation, Trench 2.

Most of the outcrop is tectonised and shattered (Fig. 7). A sample from Trench 1 (BGS Sample MPA 61989) yielded a palynological residue comprising small opaque fragments and a single specimen of a possible acritarch attributed to *Lophosphaeridium*? sp. (Molyneux 2013). This is a long-ranging genus not diagnostic of age, but it is more prevalent in Early Cambrian assemblages than in Early Ordovician, which suggests a correlation with the Malvern Quartzite Formation.

Some 10m of fresh, massive, largely uniform sandstone was exposed in Trench 12. Three small areas, each some 100mm long, of alternating mm-scale pale-coloured (3–5mm) and mid-grey (10–15mm) laminae were noted in the exposure. Sample MR9 was taken from the uniform sandstone and Sample MR10 was taken from one of the laminated areas, the thin section cut perpendicular to the laminae.

Sample MR9 is a texturally uniform, white to pale-grey, medium-grained quartz arenite comprising quartz (97%) with minor lithic grains (1–2%), altered mafic grains, oxides and silica cement (Fig. 8). Texturally, the quartz grains are rounded to well rounded (the latter averaging 0.45mm) and are clear or lightly dusted with microlites. Some grains have slight undulose extinction and many have silica overgrowths. There are two types of lithic grains (>0.1mm), both sub-rounded, polycrystalline and quartz-rich. In one group, the grains have variable straight extinction, in the other the extinction is aligned and undulose. Late-stage, thin iron-rich veins cross-cut the sample.

Figure 8 Photomicrograph of a quartz arenite from the Malvern Quartzite Formation. Sample MR9: Q = quartz grain with silica overgrowth, L = lithic grains.



Sample MR10 is also a quartz arenite, but is texturally more varied, with alternating mm-scale laminae. The pale laminae are similar to MR9 except for the absence of any lithic grains. The darker laminae, which are much finer grained, comprise quartz (98%) and contain minor altered mafic grains and oxides, but no lithic grains. Texturally, the quartz grains, which are similar to those in MR9, are well sorted and up to 0.2mm in diameter, with some clustered around larger (0.75mm) grains.

Phemister (in Mitchell *et al.* 1962) described a sample from Martley (E 17612J) as quartzitic sandstone with average grain-size about 0.5mm and a siliceous cement. The Martley quartz arenite is similar to the Malvern Quartzite of the type area in containing large amounts of very rounded, almost spherical grains of clear quartz of quite uniform diameter (*c.* 0.6mm). The Lickey Quartzite ranges from quartz arenite through subarkose to lithic arenite, and its quartz grains are less well rounded. The polycrystalline, quartz-rich lithic grains seen in sample MR9 suggest that they were derived from at least two sources, igneous and metamorphic. Groom (1902, 1910) named many lithic rock types in the Malvern Quartzite, including several that are quartz-rich, such as metamorphic quartzite, plutonic quartz, rhyolites and granite. Sweeting (1927) described felsic material that might represent volcanic igneous rocks. Groom (1902) also recorded lamination in the Malvern Quartzite. A sample of Malvern Quartzite showing very similar mm-scale laminations was noted in Malvern Quartzite exposed near Gullet Quarry in the southern Malvern Hills. Both the petrography and the palynology strongly support correlation with the Malvern Quartzite rather then the Lickey Quartzite.

Silurian — Moor Cliffs Formation

Late Silurian (Přídolí Series) alluvial floodplain red-beds exposed in the trenches are correlated with the Moor Cliffs (formerly Raglan Mudstone) Formation of south Wales and the Welsh Borderland (Barclay *et al.* 2015). These outcrop extensively around the inlier in the footwall of the East Malvern Fault and were referred previously to the Downton Series of the Old Red Sandstone (Mitchell *et al.* 1962). The strata in the trenches consist of brick red to red-brown (mainly) to purplish mudrocks with pale-green mottling. They are largely weathered to stiff red, green- and purple-mottled clay (Fig. 9, *opposite*). A thin intraformational mudrock clast conglomerate is present near the base of the clays in Trench 1. Stiff, red clay on the eastern side of the inlier in Trench 1, in proximity to the East Malvern Fault (EMF), was initially correlated with the Late Carboniferous Etruria Formation, as on the on-site geological map. This correlation was based on the interpretation of the Halesowen Formation–Malverns Complex as an unconformity and the Halesowen Formation–red clay junction as a normal stratigraphic boundary. However, with additional evidence provided by the subsequent trenching and the interpretation of both contacts as thrusts, the red clay is now considered to belong to the Moor Cliffs Formation.

Carboniferous — Halesowen Formation

The Carboniferous rocks of the site were formerly referred to as the Highley Beds (Mitchell *et al.* 1962). They are correlated with the Halesowen Formation of the Midlands, of Late Carboniferous

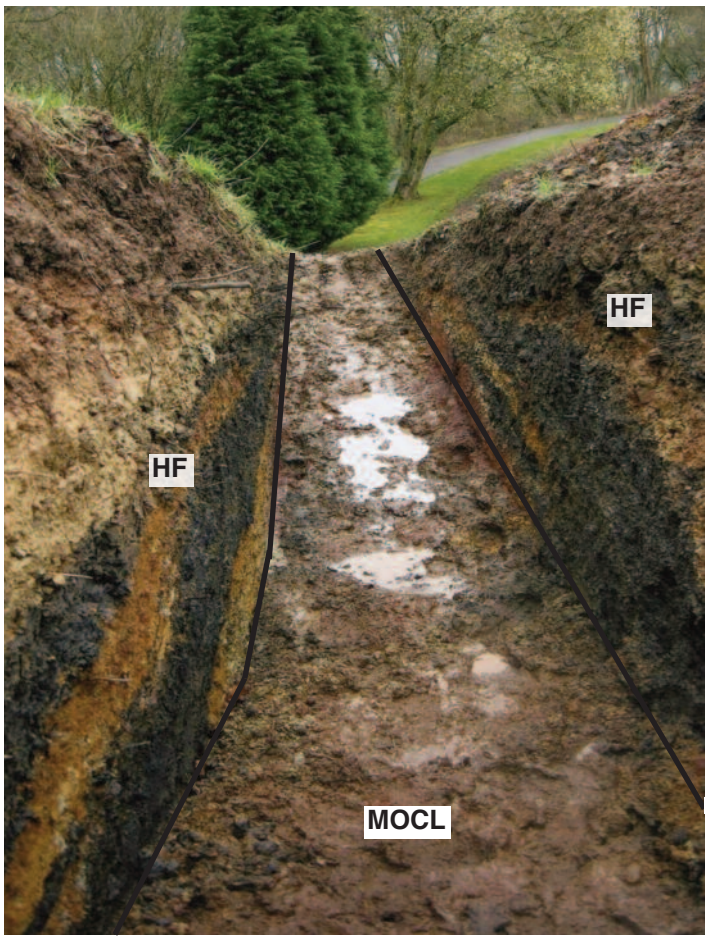


Figure 9 Red clay of the Moor Cliffs Formation (MOCL) overlain unconformably by colour-bedded mudrocks of the Halesowen Formation (HF) in Trench 1.

(Asturian) age (Waters *et al.* 2011). The work has made possible the first petrographic description of the Halesowen Sandstone at Martley and collection of a sample for palynology.

The Halesowen Formation comprises multi-coloured mudrocks with hard, fine-grained, green and grey tabular sandstones (Fig. 10). It either rests unconformably on the underlying rocks or is in faulted contact with them. The mudrocks are pale grey, pale green-grey, orange, dark grey and black, the darker lithologies being carbonaceous. The black ones are coal-rich. Colour-banding reflects differing oxidation states of the mudrocks. Petrographic analysis of samples of the sandstones, the first carried out at Martley Rock, shows them to be arkosic arenites. Sandstones elsewhere in the Halesowen Formation are described as grey-green and micaceous (Brenchley and Rawson 2006). The Halesowen sandstones have been correlated with the Pennant sandstones of the South Wales Coalfield. Both were derived from the Cornubian-Armorican highlands to the south (Glover and Powell 1996).

Palynological analysis of a dark grey clay from Trench 1 (BGS Sample MPA 61990) yielded a palynological residue comprising large and numerous opaque fragments and scarce miospores. Five definite and two possible miospore specimens were recorded. Preservation is fair to good, and all the specimens are small and relatively simple. One specimen is identified as *Lycospora*, probably *L. pusilla*. This species is not particularly diagnostic of age, as it ranges from the Mississippian into the Permian, but is consistent with a Carboniferous age (Molyneux 2013).

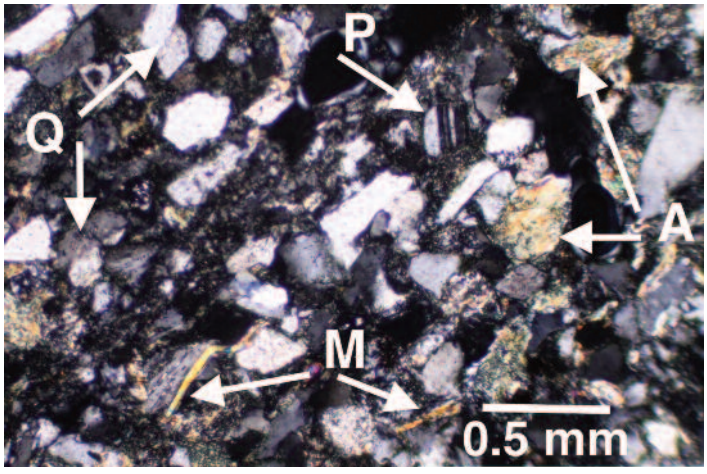
A representative sample from Trench 12 (MR11) is a very fine-grained, medium grey arkosic arenite comprising quartz (70–75%), chloritised mafic mineral(s) (10%) and oligoclase (5%), with minor muscovite and oxides (Fig. 11). The matrix is locally iron-stained. Texturally, the quartz grains are sub-rounded to angular, with a few microlites, and some slight undulose extinction. A few grains have silica overgrowths. The oligoclase is euhedral and fresh, except for some slightly corroded ends. The muscovite flakes are bent around the surrounding grains and partially chloritised. The mafic grains are unidentifiable because of extensive chloritisation, as also is some of the matrix.

Triassic — Helsby (Bromsgrove) Sandstone Formation

Traditionally named the Bromsgrove Sandstone Formation of the Sherwood Sandstone Group, this has been renamed in a recent rationalisation of nomenclature as the Helsby Sandstone Formation (Ambrose *et al.* 2014). It was proved in the trenches to the east of the East Malvern Fault. Only short sections were excavated, in which it consists of soft, weakly consolidated to weathered and unconsolidated, orange-brown, fine-grained sandstone.

Figure 10 Interbedded sandstones and mudrocks of the Halesowen Formation in Trench 7.

Figure 11 Photomicrograph of an arkosic arenite from the Halesowen Formation. Sample MR11: Q = groups of quartz grains, P = a plagioclase, M = muscovites, A = altered mafic grains.



Structure

Groom (1898, 1900) described the structurally complex exposures in the former pit. He noted that the Precambrian rocks had apparently been thrust over the Cambrian quartz arenite, with subsequent folding along a north-and-south axis and further thrusting. About 42in (*c.* 1.07m) of quartz arenite then exposed was shattered and arranged in the form of a plicated anticline or anticlinal dome, dipping to the west and east and showing a tendency to a quaquaversal arrangement (i.e. sloping downwards from the centre in all directions). Groom's illustrations show a section about 2.9m long and 2m high, comprising diorite at the top overlying schists, which surround quartz arenite forming a corrugated anticlinal structure.

In 1985 one of us (WJB) recorded small exposures of shattered and disturbed rock in the northern part of the pit, including a green, micaceous, schistose shear zone, white sheared clay gouge, pegmatitic, felsic quartz-feldspar rock with a little mica and a small outcrop of greenish dioritic rock (Barclay and Rathbone 1990). These exposures are probably some of those recorded by Groom (1898, 1900). The trenching in the present study revealed them to be part of a steeply dipping to vertical fault zone named the Martley Rock Fault (MRF; Barclay *et al.* 2012). This is exposed in Trench 2 to a depth of *c.* 1m to 2m; elsewhere, it is only seen at rockhead and represented by zones of sheared meta-igneous and quartz arenite debris. Over most of the inlier, this fault separates two different successions, with the Malvern Quartzite Formation confined to its west and the Malverns Complex confined mainly to its east. In Trench 2, the fault comprises a complex zone of tectonised quartz arenite and meta-igneous rock. There is little evidence of the low-angle folded thrust between the two units and plicated anticline recorded by Groom (1898), except perhaps for one example (Fig. 12), which lies in the backwall of the old pit and may have been the exposure on which Groom based his interpretation. To the south-west of the MRF, in Trench 1, the Malverns Complex is thrust over the Malvern Quartzite Formation by a flat-lying thrust. This structure superimposes much fractured quartz arenite of the Malvern Quartzite Formation on clays of the Halesowen Formation.

Figure 12 Sheared meta-igneous rocks of the Malverns Complex (MvC) overlying and faulted against quartz arenite of the Malvern Quartzite Formation (MQ) in the Martley Rock Fault Zone, Trench 2 (white label is 80mm).

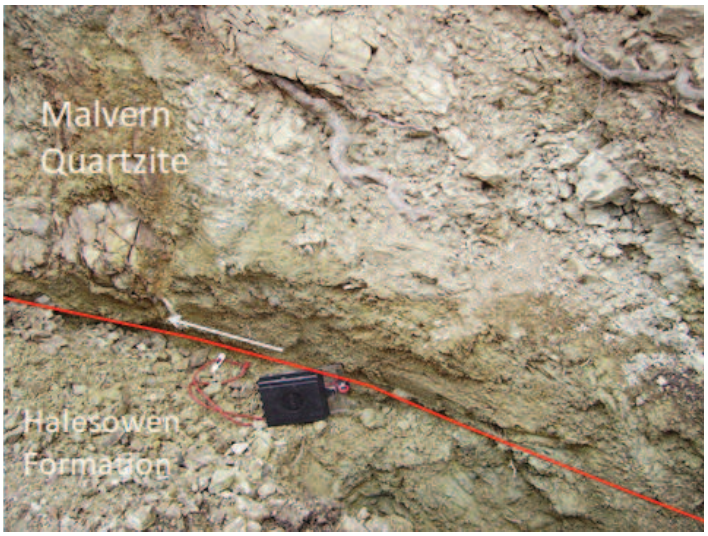
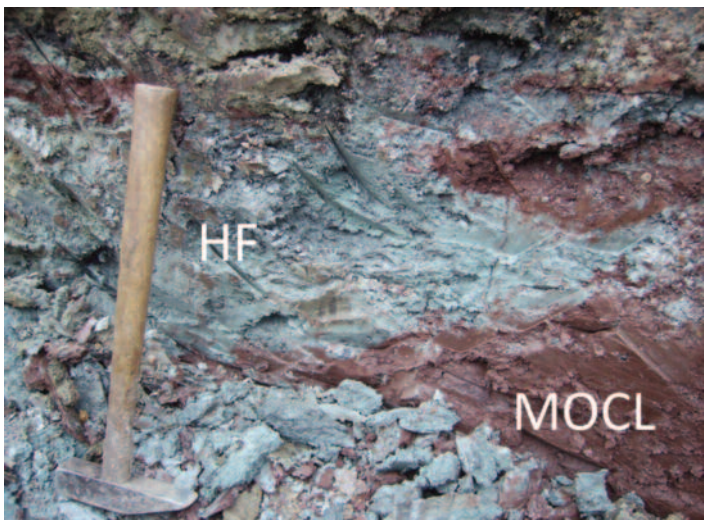


Figure 13 Shattered quartz arenite of the Malvern Quartzite Formation (MQ) thrust over mudrocks of the Halesowen Formation (HF) in Trench 1.

Trenches 1, 6, 7 and 11 proved that the Malvern Quartzite Formation exposed in the inlier comprises a newly discovered, flat-lying WNW-directed thrust sheet overlying the Halesowen Formation (Fig. 13). The eastern boundary of the Malverns Complex, as seen in trenches 1, 4 and 9, is interpreted as an east-facing, west-directed thrust with the overlying thrust sheet comprising mudrocks of the Halesowen Formation. Small steps in the thrust plane may represent small-scale extensional normal faults related to the East Malvern Fault very close to the east. The junction between the Halesowen and Moor Cliffs formations, the latter present in a narrow strip in the immediate footwall of the East Malvern Fault, is also interpreted as a tectonic one, with east-facing, west-directed thrusting producing a complex of inter-sliced red (Moor Cliffs Formation) and grey (Halesowen Formation) clays (Fig. 14).

The trenching has accurately pinpointed the location of the East Malvern Fault. This fault was shown by seismic studies (Chadwick 1985; Chadwick and Smith 1988; Barclay *et al.* 1997) to be one of a series of Variscan transpressional thrust faults reactivated as a Permo-Triassic extensional basin-margin fault.

Figure 14 Tectonically inter-sliced red clay of the Moor Cliffs Formation (MOCL) and grey clay of the Halesowen Formation (HF) in Trench 9.



A footwall short-cut thrust model

In a regional context, the Martley inlier lies on the Malvern Axis, in the footwall of the EMF. The EMF (termed the Malvern Line by Pharaoh *(this volume p35)* forms the western boundary of the Permo-Triassic Worcester Graben. The Malvern Axis exposes Precambrian meta-igneous rocks of the Malverns Complex in its type locality of the Malvern Hills to the south of Martley, as well as Silurian strata of Llandovery to Přídolí age. Close to the north, the Abberley Hills expose Silurian (Wenlock to Přídolí) strata, arranged in a series of stacked thrust sheets separated by steeply dipping reverse faults named by Mitchell *et al.* (1962) as the Cockshot Hill Thrust, Penny Hill Thrust and Rodge Hill Thrust. These (the Malvern Axis thrusts of Chadwick and Smith 1988, fig. 2b), converge southwards in the vicinity of Martley. Compressive, contractional stress, resulting in folding and thrusting along the Malvern Axis, is summarised in Worssam *et al.* (1989) and in Barclay *et al.* (1997). Structures include the Herefordshire Beacon Thrust, parts of the West Malvern Fault, the Storridge Anticline and the Ankerdine Thrust.

Brooks (1968) interpreted the Precambrian basement to be at probably over 1,000m depth near Martley. He suggested that the axis of the major fold of the Malvern axis (responsible for the Malvern Hills) lay east of Martley in Armorican (Variscan) times and was subsequently lowered by movements along the East Malvern Fault. In this interpretation, he concluded that the Martley inlier possibly comprised material thrust westward from the axial zone of the major fold prior to the formation of the Triassic Worcester Graben. On this basis the structure at Martley is closely comparable to that of Herefordshire Beacon and Chase End Hill in the Malverns. Brooks's (1968) model was confirmed by the British Geological Survey's Kempsey Borehole (Whittaker *et al.* 1980) and by subsequent seismic studies (Chadwick 1985). Chadwick and Smith (1988) noted that the precise timing of the compression and reverse displacements on the Malvern Axis is difficult to assess, but suggested that early Palaeozoic (Caledonian) episodes may have been initially responsible. This is supported by the marked thickness changes in the Cambrian strata of the Malverns, attributed by Brooks (1970) to pre-Llandovery tectonism.

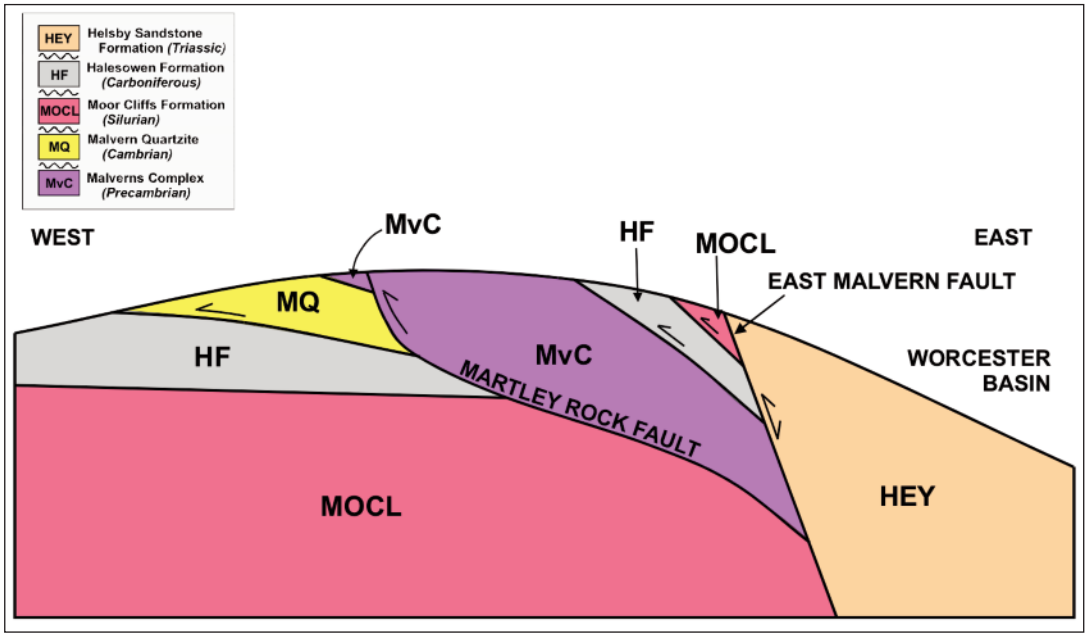
However, a significant component of Variscan (Late Carboniferous) compression is clear, both from the seismic and field evidence. Chadwick and Smith (1988) commented that whereas the Caledonian (?Acadian) compressive stresses were probably oriented NW–SE, and that the Variscan stresses were oriented roughly N–S, movement on the N–S ('Malvernoid') Malvern Axis and East Malvern Fault were likely to have had a considerable oblique strike-slip, transpressive component. That none of the structures have been imaged to great depth in the seismic studies suggests that they are relatively steep, supporting a model of a major flower structure that produced Palaeozoic uplift of a tract now underlain by the Worcester Graben. Permo-Triassic extension and that negative inversion of this tract resulted in the Worcester Graben. Pharaoh *(this volume p35)* provides a comprehensive account of the complex tectonic history of this tract.

Barclay and Rathbone (1990, fig. 3a) sketched a thrust model for the Martley inlier. The new trenching data has provided refinement of this model. McClay and Buchanan (1994) illustrated experimental laboratory models, as well as actual examples, of the effects of compressive inversion of an extensional sedimentary basin. In both laboratory modelling and actual examples, while much of the compressive stresses are taken up by reverse movement on the basin-margin fault (e.g. the EMF in the case of Martley), a footwall short-cut thrust or fan of short-cut thrusts can splay off the main fault. This provides a mechanism and model for the thrust faulting seen at Martley in the footwall of the EMF (Fig. 15). Subsequent Mesozoic (Permo-Triassic) rifting and extension was taken up principally by this fault, to form the western margin of the Worcester Graben.

Geoconservation

The excavation of the trenches at Martley Rock has resulted in raised interest in the local geology. A series of evening classes led to the formation of the Teme Valley Geological Society *(Cropp, this volume p29)*. In 2011 the community secured European (LEADER) funds aimed at making the geology of the parish better known and more accessible. Under the conditions of the funding, Trenches 1 and 2 will remain open until 2023 as a 'Geosite Visitor Attraction' (parties of more than 10 people should book in advance by contacting the landowners at Cob House Fisheries). The site is thus of geoconservational importance in providing man-made exposures that help the understanding of the subsurface geology. The funding also made possible the production of an audit of the local geological sites and led to Martley being accorded 'European Geo-Village' status.

Figure 15 Schematic west-east cross-section across the Martley inlier to illustrate a footwall short-cut thrust model.



Conclusions

The trenching work at Martley Rock has resulted in greatly improved accuracy of the geological map of the Martley inlier, and an increased understanding of its structure. In particular, the study has shown that the structures described by Groom in 1900 lie in a fault zone, the Martley Rock Fault. Also, the trenching has shown that a quartz arenite sheet lies on a previously unknown low-angle thrust fault. Limited palynological evidence obtained suggests that the quartz arenite can be correlated with the Early Cambrian Malvern Quartzite Formation. Petrographical study of the meta-igneous rocks of the inlier confirms their correlation with the Late Precambrian Malverns Complex. The inlier is interpreted as a complex of Variscan thrust sheets in the immediate footwall of the East Malvern Fault. The thrusts are interpreted as footwall shortcuts from the EMF.

The work on the site has engendered increased interest in geology, and has been seminal in the formation of a new geological society and in the establishment of Martley's 'European Geo-Village' status.

Acknowledgements

Much of the trenching at Martley Rock was funded by the European LEADER programme. Grateful thanks are due to Paul Olver for instigating the original trenching in 2010 and to John Nicklin for organising the 2012–14 trenching; also to Elliot Carter for his assistance with the petrography and to Moira Jenkins for her help throughout the work. The site owners Helen and Rob Taylor, and farmer Richard Bray are thanked for their willing cooperation.

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Small is Beautiful

David Cropp

The Teme Valley Geological Society

As you can see from the title, this talk was called 'Small is Beautiful'. The sole prop I had for this presentation was an empty beer bottle — small indeed! Some of you reading this may think 'shame', but that's the way it was.

This was not a talk that I would call a 'DBOP', or 'Death by Overhead Projection', because I recognised that the Summer Symposium was going to have a whole range and series of complex talks and lectures throughout the weekend, which involved looking at the screen, or reading the subsequent publication of them — but this one involved looking at me, or reading this article, which might be worse, but we'll see where we go with it.

In this article I'm going to present the community of Martley Worcestershire and talk you through how we came to where we are today, into something that is quite an exciting and certainly a European-wide, if not a world-wide, concept.

Now the village of Martley started about 5,000 years ago, and those of you who are lucky enough to come out to visit, or those of you who are coming later, will find that above the village is an area called Berrow Hill, which was in fact an Iron Age encampment. Martley was settled then, possibly earlier, and has been continuously lived in since then. The reputation or legend is that Martley is the oldest continuously lived in and settled village in England — there's no proof of that, but we can claim we are. Legends are always the best way to claim.

There are reasons for that settlement; some of those reasons are political, some of those reasons are social and one or two of the reasons are in fact geological. Now that's quite interesting when you think about it, to say that people settled for reasons of geology. Somewhere in the deep mists of time, somebody came to the Martley area and decided it was the right place to settle.

When you come to the community you'll find it a bit odd as to why people said this. Is it on the top of a hill? No, it's not. Is it by a river? No, it's not. Is it by a crossroads or main route to somewhere? No, it's not particularly anywhere. So why did people settle in the community which is Martley? One of the reasons was that it was far enough away from trouble — it sits in a bowl (which I'll describe geologically later on), and anybody crossing the landscape would come along the hilltops for visibility and safety.

The area in which our community sits was far enough away from every invasion, since Roman times, that when every invasion was over, Martley seems just to have turned its market stalls around, changed the lettering on the side, and sold produce to the next invader. This is not as fanciful an idea as it might sound.

There are records of Roman coins being found and one or two of the place names that still exist in pockets in the community are of Celtic origin, so we know that they survived. We know that there were contacts with Angles and Saxons, and they survived that too, and we know that, of course, eventually the Normans arrived in Worcestershire. In fact the Bishop of Worcester was one of the only two Anglo-Saxon bishops to remain in place after the Norman Conquest, because by the time the Normans reached Worcester it was all over. So in a sense, Martley was part of that successful sequence of every sort of invader. As you can see we are very pragmatic about what happens to us.

But, as I suggested earlier, the reason that Martley was settled is certainly something to do with the geology. Somewhere there was an 'ur-geologist', or a Neanderthal who had the instinct to recognise that it was a good place to settle.

Martley is bounded on the north by a series of what we can call fault cliffs, and I'm not being technical here. The people then settled below those, in that area, in what was very much a gap in the fault line. The village faces south and the east. In fact, if you look at it on a map you'll see the north–south fault line and that most of the village sits in the bowl where the fault line is fractured. It's a perfect environment to grow anything. It was a significant fruit-growing area, not just like Evesham and its plums, but the whole range of fruits. At one time there was a blackcurrant processing and jamming factory in Martley. Originally, damsons and damascenes (which was the Roman damson) grew, and still grow, in the area — any fruit, even vines. Recently I visited a vineyard just at the far end of the Parish; where they now have 3,500 vines facing south, and it is highly productive, mainly because of its geological position.

It was a stable village. It had some very strange features. People who lived there also worked there, even in recent times. Obviously nowadays there is more of a commuter element to it. People come and go, and people retire there, but originally it was a very stable village; the workers lived there and they mainly worked the land because the land was just so productive.

When I first came to Martley, about 40 years ago, an old man in the village showed me a photograph of somebody in a rowing boat where our houses were about to be built, which suggests what happens when you live in a bowl! We had heavy rain in those days and all the rain poured off the hills into the bowl of Martley, filling the centre of the village. I can remember one night coming out and seeing a brown river flowing through the village. That has now changed, as drainage was installed later, but still the village gains from being in this bowl-like area backed by a north–south spine. So you can understand geologically why people would want to move there.

So, dear reader we rocket on to 1839, the significance of which everyone will well know, was what? You see I forgot to mention that I do sometimes use my reader or my audience to fill in missing facts.

Actually it's quite interesting. That is the year that Sir Roderick Murchison visited Martley and I'm very, very disappointed that nobody in my presentation, or reading the article, knew that! But he visited Martley. There is no local record of it but in his work on the Silurian System he mentions that he came up to Martley and saw something that he felt was geologically important and wrote it up, but to the community of Martley at the time it meant absolutely nothing at all.

If you come to Martley you'll discover, all around the village, that there are flexible examples of the local people and their ability to use and reuse local stone. I'm certain that in times past people just dug a hole in the ground and found what sort of stone was there, and if it wasn't the right sort of stone (because Martley has such a wide range of different types of rock) they just moved on somewhere else and dug another hole until they

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found the type of stone they wanted, be it limestone or sandstone or metamorphic — whatever. Certainly in the centre of Martley, in some of the curved walls, you can still see the red sandstone blocks that were probably taken from the original 6th-century Saxon church and reused. It would be a good project for someone to go around and find all of these stones, most of which are on view on the main bend into Martley. People quarried stone all around Martley. An example is St. Peter's, a lovely medieval red sandstone church.

Here we have a community that clearly used its bedrock landscape for its best purpose. So we now leave 1839, and we come forward to 2010 when — I cannot remember exactly when — a fortuitous meeting took place: we were approached and told, look, you have significant geological features in your community, and if Sir Roderick thought that, so should you.

Let's be honest. We are a tiny community; we do not have herds of wildebeest, we do not have thundering waterfalls, but apparently we do have significant geology, although we did not realise it at the time. I put it to you that not all geology is in GeoParks and National Parks. When you think about it, it's a complete fallacy that we can only have 'valid' geology on a grand scale. Geology on a grand scale is very beautiful and very exciting, but geology is quite literally everywhere.

Dr Paul Oliver came to us and said "Look, you've got some excellent and unusual geology, historically important, let's explore it.", and in 2011 The Teme Valley Geological Society (TGVS) was formed, now one of the biggest and most active geological societies, and, uniquely perhaps, one with hardly any geologists in it. We have 90 members, and 350 e-contacts, and it's thriving, with full, student (free), and distance (half price) membership rates. The TGVS now has its own Members' Library with an extensive collection of books and materials to loan.

We have very much come from the local community direction to conserve the geology, which we have, drawing on professional expertise to support us. Initially we were particularly indebted to the tireless and continuing support given us by The Hereford and Worcestershire Earth Heritage Trust, and later for the active and ongoing support from The Geologists' Association. But our geological sites were going to be community driven, to the point where we were able to convince the LEADER Programme in Worcestershire, primarily an EU programme, to fund us £26,000, basically to dig a hole in the ground.

I can still remember the reports of the actual interview, during which there was a great deal of 'business sucking of teeth', because EU programmes tend to build village halls, play areas, facilities for young people, facilities for old people, but not very often to dig holes in the ground. Fortunately they took that risk, and it paid off because it became an iconic project initiative and was recognised as being an imaginative use of funding.

We had expertise coming in and we excavated and developed the Martley Rock area — it was a brilliant experience! Our LEADER group clearly discovered that they had prompted a project for something that was unique and amazing. The Worcestershire LAG (Local Group) members obviously saw themselves as being part of that push forward into new areas and they received a lot of national prestige for having funded that hole in the ground.

As a result of their 'feel-good factor' we managed to convince them to give us a second tranche of funding of £10,000 to dig a second set of holes in the ground.

Figure 1 Digging the first trench at the Martley Rock site.

And I can remember those days on the second trenching of the Martley Rock area, across the field next to the first Martley Rock site (Fig. 1). We hired a digger driver that day (who probably spent his days digging the usual stuff that farm diggers dig) and he, for that day, had the wonderful and unique experience of having professionals around him to tell him where to dig holes in the ground. I believe he had the best experience of his life because he kept exposing rock formations that, as far as we know, had never ever been seen. He dutifully drove his digger up and down the field, leaving huge heaps at various places like a giant mole. As he had so much excitement, he has so far never sent us a bill! So that's the sort of person you want to get on board if you're going to do conservation.

As a community group we had found this project a spectacular example of what we as a community — and in fact you with your communities — can achieve with your local geological features. Now we move the description on a little further.

We have a Geological Society prefaced with 'The Teme Valley', rather than with 'Martley'. From the start our instinct was to not make it so focused on just one community. Eventually we hoped we would go outside our community to discover, develop and promote other geological sites, and to expand from where we were. We commissioned and published an audit of the geological sites in Martley. For us in our small parish we have more than 40 geological sites. Now that is significant. We're not talking about sites that look the same and are just in a different location; they are completely different geological sites, both in age and formation, within a small footprint of a parish measuring five by two kilometres.

Most of these sites are on private land, so you can consider the local politics. But there's a kind of flip system at work here; you begin to get landowners and property owners who are quite happy for you to come visit; bit by bit it becomes a kind of inverted thinking from those who have not yet given the blessings of access — why haven't you come to see my private site? It truly does happen; there's a kind of cascade effect, and for those of you who visit I don't want to put your hopes up too far but there is certainly one site where the owner on occasions offers champagne to visiting geologists.

This does encapsulate what small communities can do in terms of positive geoconservation. If somebody has an accessible site and you are professional in the way you approach them, they are likely to be more than happy to be the custodians of unique, valuable and important heritage for us to see; and now many of our landowners and property owners are very happy for that to happen.

At the start it was slow — they always have this apocalyptic vision of hoards of people tramping, a bit like something out of *The Lord of the Rings*, an army marching and crushing everything in its path. But they began to realise that we were working with people who were both interested in terms of geoconservation, understood what they were looking at and were prepared to come and take care of what they could see in front of them and what they were exploring. So that's expanding and is still expanding, and it makes it still very exciting — and our discoveries continue.

The TGVS does a number of things that may be slightly unusual; we have a Committee that is based on a Japanese flattened-management style, which means that any of us can take any role and, because we're all doing different things as volunteers, we swap a whole range of roles; we just switch them as we need to, to meet the needs of what we're doing at any time.

We have a quarterly meeting, which usually involves wine and cheese, and has a diacritical approach to decide where we're going forward with the development and conservation in our community: what we need to do, what we can do, what we can't do, but very much 'blue-sky' thinking. As a society we hold full monthly meetings, provide courses, sponsor new geological projects, and are developing field trips.

To give you some examples:

Last year we explored the idea of building a new Geo-Gateway Centre in the centre of our community. We'd reached the point of designs and mapping it, we had an architect on board and that's still held.

We still have the view that there is more excavation to be done. I still remember my quartzite reef. I have a quartzite reef, which was subsequently reburied; I want to go back and find my quartzite reef, because apart from me nobody was there when the digger dug it up. There it was, and I want to go back and excavate that again.

I have also a personal dream of an Underground Centre at the Martley Rock site, matching the Interpretation Centre at the Capelinhos Volcano in The Azores. I want one of those iconic experiences in Martley to show all the rock formations.

But at that point in our Committee Meetings, they usually 'recork the bottle of wine'.

When you look at it from a community aspect rather than just from a geological aspect, all sorts of things come into play, which probably don't cross our minds as professionals. We guide 'Geo-Ambles', which, if you understand, are not for you, but are for ordinary people and non-geologists, and are absolutely ideal on a summer's evening to go 'a-wandering' on a led walk, to see some of our geological features (Fig. 2). It's a relaxed semi-formal way to experience geology.

Fully supported by The Geologists' Association we've hosted two Geo-Labs in Martley. Geo-Labs are for people who have no experience of geology. We set them up in the village hall, and conduct experiments: it's one of the dirtiest days you'll ever see, with sand, mucky water and bits of glue everywhere — creating a whole range of experiments aimed at ordinary folk, to insert some of those important first geological concepts in their minds. It's pitched at families, and they just pay a minimal fee, and just have a day 'doing geology', followed by a Geo-Amble to see one of our sites.

Figure 2 A Martley village guided 'Geo-Amble'.

At the start of our geological journey we also created 'Rock Boxes' for our local primary schools in the villages along the Teme Valley. This is about to be superseded by an new initiative of Rock Boxes, designed by The Geologists' Association, to compliment UK Key Stage II, and that in partnership with them we will be linking once more into our local primary schools.

So what we have been looking at is how can we generate within a community the type of drive for its residents to recognise their geology, to appreciate their geology and to be stewards or custodians of something that is valuable. It's not a Geo-Park; it's not a National Park — it's one small community. The politics of that — I think you can see where I'm coming from — is that a lot of the parks internationally suffer in terms of the expense of the management and the infrastructure they have to set up to run these huge areas. In Martley we just do what we can do, and we do a lot, an economically effective way in which you can develop geological features without massive infrastructure capital and ongoing costs.

I often call some of the projects that I see 'Champagne Projects' — the big, bold and beautiful, where a lot of capital goes into them, but after that it has to be managed and maintained. And that's where the system really runs into difficulties. In our programme we do what we can, we pay what we can, we organise what we can, because we are all volunteers and we just

love the geology in our community. The community, too, has come to appreciate and love the geology, which is a wonderful place to find yourself as an organisation, because it means that almost everything is self-driven and self-managed. I see that as the future for a lot of development in terms of a whole range of fields, not just geology.

So we've got The Teme Valley Geological Society, we've got our sites, we now have orientation boards, apps, and we have walks leaflets published and printed. Those who are lucky enough to come here and haven't been swayed by the siren call of the Malvern Hills will have free access to what we have to offer. We have that series of publications available in the centre of the village, so that anyone arriving in the village can just take what they wish and go on the walks, because we want our geology to be accessible to anybody who comes to see us.

Of course if they are coming to us, they may spend the day with us, so economically they are adding to the community and that's just as important.

And this is where the beer bottle comes in — you've all been staring at it (if you were at my presentation) or remembering it at the start of this article (if you are reading it) — I can tell you are transfixed by it. As a custodian of geological heritage you can do all sorts of different things and they don't all have to be geological. This, you'll be interested to know, was a beer called Martley Rock (Fig. 3). Last year I could have recommended it to you; a local micro-brewery decided that, yes, they would produce a Martley Rock light beer — it had to be rebrewed five times (so you're talking about five times 800 bottles) and the bottles were drunk in one summer, because every local, every tourist, every geologist, every walker had some. To celebrate, we held a three-pubs walk, which ended up at the brewery where it was made.

Figure 3 Martley Rock light beer shop display.

But that's the sort of thing that brings geology down to a safe level for anybody and everybody, and from there you hope that you can promote their understanding of more about the geology that they are discovering, and then be encouraged to go out and expand their experience.

Now we come to the concept of the 'Geo-Village'. At the same time as the TVGS was gearing up to work in Martley to create very much a Geo-Village concept, it was developed further in Europe through a European Grundvig Project with three other communities: Sentheim in the Haut-Rhine in France, Eichstätt in Bavaria in Germany, and Boyabat in Sinop Province in Turkey. Three communities that already had different assets as communities promoting local geology.

Since then we have developed the concept and presented the Martley Geo-Village experience in Torquay at the '7th International Geo-Parks Conference', in the Azores at the '14th European Geo-Parks Conference', and more recently at the '9th Pro-Geo Congress in Poland'. We believe that in a time of austerity in many countries, geology can be exploited, not in terms of mining and extraction, but in terms of micro-tourism, within communities that do not have much on-going investment because they don't lie in significant geological or tourism areas. Thus, the Geo-Village.

This is a way for communities to take responsibility, to develop and to gain from their own geological perspective, and it's one that has resonated with us. We travelled to Poland in October 2018 to the village of Dobkow, which is in Lower Silesia, to visit and celebrate them as the first Polish Geo-Village. All over the countries of Europe, and worldwide, we hear interest in the idea that communities with significant or important geology being able to promote their geological development for themselves. We already have other potential communities coming on-stream this year in Crete, Turkey and the United Kingdom.

One of the other important points is that Martley is a 'Walkers are Welcome' village. All the footpaths in Martley — that's about 65km of them — are open, marked and maintained. We were nationally the thirteenth community and first village that received 'Walkers are Welcome' status. Again, that takes negotiation with landowners, but landowners recognise that if you are responsible for your landscape, even if you don't own it, they too can recognise the importance of allowing people to come and spend time and money in the community.

So the Geo-Village concept fits well with a welcoming community, a community that has significant geological features of importance, regardless of size. Any potential Geo-Village is going to have some level of infrastructure; the ability to arrive there, the ability to stay there, the ability possibly to shop, the ability to have food or to purchase local produce, the ability to have the leaflets and follow marked trails, to have some kind of central focus so that people can see what they are coming to see, and a website. And lastly, local people prepared to take responsibility.

If you look now up www.geo-village.eu it should bring you to The Teme Valley Geological Society, where you can see a full range of what we are doing. We have a website that expands all the time; it has blogs and serious pieces of information on work in progress, and events, so that people can quite literally see us

before they come to us, because that's what we want. We want people to be able to experience the community, come to it and enjoy it.

But think about the fact that we merely started with two grants, end of story. We have not had any other grants since then and all of that ongoing work has now been generated from within the community, and supported by outside professional individuals and bodies, as already mentioned. I think that's quite significant, because as small organisations and communities we tend to look outside for where we're going to get the money to do something, but I think with Martley it's slightly different, it has historically been a very self-supporting community.

Geology for communities can be aspirational and for me that is a key. This is 'can do'; we don't believe in 'can't do', we seriously believe in 'can do'.

I mentioned before that we call ourselves The Teme Valley Geological Society. The Teme Valley runs north-west from Worcester right up to Ludlow and beyond. All the way through there is a whole range of geological sites, so we wanted in the end to have some ability to spread. We have begun to expand into one or two sites; one is Southstone Rock, a very significant outcropping of tufa, historically very famous.

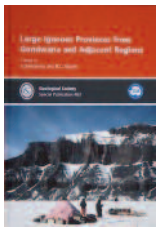
There are also many ways you can link local craft and produce with geology. We are hoping (again this is after that bottle of wine) to promote a whole series of varietal blackcurrant orchards running up the Teme Valley, linked with geological sites … it's coming, it's coming. This is just one of the 'blue-sky' ways in which local communities can thrive in areas that are not yet significant as tourist destinations.

Martley and the area out west of the Severn has suffered and gained from being left out. It's the smaller part of the county, it's a buffer in The Marches area, running north–south through Shropshire and into Herefordshire, and somebody once described it as an area of England that 'doesn't shout but sings'. I thought that was a wonderful description of the area in which we live — it sings. It doesn't have the kind of Jurassic Coast or Cheddar Gorge shouting, it just sings. I am sure you can appreciate that.

And we're still discovering ourselves and our history linked with the geology of the area, most recently the footprints of iron smelting. We discovered that there were a series of iron smelters who fell out of work west of us, who moved through us, made their limestone kilns and very primitively cast iron pig-ingots, which they then took over to the Severn to be floated off, so they could scratch a living.

That encapsulates Martley. I do encourage you to visit, I do encourage you to look it up on the web, I do think there's a whole range of things to do with this community, which I think are valuable both socially and economically, from the perspective of tourism particularly, but also geologically. I believe you will probably be coming in the future, and, if you are, contact us and we will provide you with free guides and take you to the sites; we may even take you to the site owner who produces the glass of champagne if you're lucky, but certainly we welcome people looking us up, looking at www.geo-villages.eu and saying "yes, I'm going to go and visit that and I want to see x, y and z"; and we as a group, in Martley, will be both welcoming and will try as far as possible to provide you with what you want.

Book review



Sensarma, S., and Storey, B. C. (eds) 2018 *Large Igneous Provinces from Gondwana and Adjacent Regions*. London: Geological Society Special Publication 463 (ISBN 978-1-78620-325-0; 268pp; hardback £90.00)

Large Igneous Provinces (LIPs) — boring old basalt I hear you say; but it is not so. Yes, there is quite a lot of basalt involved, but the rock types found in the LIPs extend to carbonatites, granitoids and rhyolite. This book is probably not for the geological novice, but for those with a basic background there is much to be learned from this collection of 11 research papers. 'Gondwana', in the context of the book title, covers those areas that were part of the Gondwana supercontinent, as many of the LIPs postdate its breakup.

The introductory paper is a good lead in to the rest of the papers: the major Gondwanan LIPs are listed in a table giving their location, what sort of area they covered, how old they are and how long they took to erupt. Also included is an 'overview of the volume', which is worth checking out just to see which of the papers you would want to read first.

Whichever branch of geology you enjoy there is probably something in this book that will grab your attention. The geochemist is well catered for and, even though chemistry is not my forte, it was fascinating to see in the many tables and graphs the composition of the rocks, including the rare earth elements that are present in the carbonatite rocks. I think the whole of the periodic table is represented in this book. For those who like a more visual representation there are field photographs, geological maps, stratigraphic columns, photomicrographs and diagrams showing the processes thought to have initiated LIPs. Of course, no one is going to just 'look at the pictures', and with just a little geological knowledge, the text, in the main, is not too complex and quite interesting. There are plenty of descriptions of the methods used in analysing and dating the rocks and what they can tell us about the mantle processes that generate the different LIPs — there is speculation about whether mantle plumes or non-plume processes underlie the initiation of some of the LIPs.

This is a book that I am still dipping into and shall continue to do so until I have read all of the papers fully. Maybe I shall find just that titbit of information to help me in my further studies with the Open University.

— Linda Morley, BSc (Hons) in Natural Sciences with Earth Sciences. Continuing student currently undertaking the MSc in Earth Science, doing the final module (S810) this year

Book review

Németh, K., Carrasco-Núñez, G., Aranda-Gómez, J. J., and Smith, I. E. M. (eds) 2017 *Monogenetic Volcanism*. London: Geological Society Special Publication 446 (ISBN 978-1-78620-276-5; 382pp; hardback £110)

This Special Publication from the Geological Society brings together developments presented in the last decade or so, mainly the last two meetings in the IAVCEI International Maar Conference series. As the opening review makes clear, such small-scale volcanic systems are the most widespread type of volcanism on Earth, despite most of the attention given to their polygenetic counterparts. This includes occurrence in all of the major tectonic environments — many are satellite vents associated with polygenetic volcanoes, though the vast majority are part of extensive volcanic fields with distinct vents, cones or calderas. A useful figure of global locations with this information is provided early on, and the subsequent 13 papers discuss aspects of most of these locations (bar Western Europe), with a focus in the second half on the monogenetic fields of Mexico and South America.

Historically, certain maar diatremes have received attention owing to their xenolith-rich products, which not only open a window to mantle composition and processes, but are also known to bring diamonds to the surface in certain localities. Two of the papers focus on the nature of kimberlite pipes responsible for such xenoliths, and how they compare with either their polygenetic equivalents (kimberlites include both mono- and polygenetic examples) or basaltic maar-diatremes.

Other papers consider the eruption dynamics in different settings, geometric analysis of surface structures to infer process, a brief foray into geophysical modelling for the enigmatic Isla Isabel (a small island off the west coast of Mexico), and compositional analyses of the various products of monogenetic fields in Central and South America.

Overall, I was incredibly surprised at the sheer diversity of all the above shown in monogenetic volcanism. Previous reviews have emphasised the need for a coupled approach when considering the classic volcanic parameters, in order to understand small scale volcanism, something that is not quite met in this collection. Much of the research presented is simply working towards appropriate classification of many aspects — it would appear that study of monogenetic volcanism is still in its infancy.

This doesn't necessarily make for a collection that builds nicely or has a unifying aim, though any perceived lack of coherence may also be to my own difficulties with reading such a meaty and varied text. The figures included were presented well and the use of colour for many of them was always employed where appropriate.

— Tom Perkins, continuing OU Earth Sciences student

The complex tectonic evolution of the Malvern region: crustal accretion followed by multiple extensional and compressional reactivation

Tim Pharaoh

British Geological Survey, Keyworth, Nottingham, NG12 5GG (tcp@bgs.ac.uk)

Abstract

The Malvern Hills include some of the oldest rocks in southern Britain, dated by U-Pb zircon analysis to *c.* 680Ma. They reflect calc-alkaline arc magmatic activity along a margin of the Rodinia palaeocontinent, hints of which are provided by inherited zircon grains as old as 1600Ma. Metamorphic recrystallisation under upper greenschist/amphibolite facies conditions occurred from *c.* 650–600Ma. Subsequently, rifting of the magmatic arc (c.f. the modern western Pacific) at *c.* 565Ma led to the formation of a small oceanic marginal basin, evidenced by basaltic pillow lavas and tuffs of the Warren House Formation, and Kempsey Formation equivalents beneath the Worcester Graben. By Early Cambrian time this juvenile crust had stabilised sufficiently for thick quartz arenite-dominated sequences to accumulate, followed by mudstones in mid- to late-Cambrian time. In earliest Ordovician time, subsidence accelerated in a rift basin east of the Malverns, but was terminated by accretion of the Monian Composite Terrane to the Gondwana margin. Rifting led to a microcontinental flake ('East Avalonia') breaking away, eventually to impact with Laurentian terranes on the other margin of the Iapetus Ocean in Early Silurian time. Minor inversion of the floor of the Worcester Graben might have occurred during the Acadian (Early Devonian) deformation phase, but more significantly, during the Variscan (end Carboniferous) Orogeny, when a 'Rocky Mountain Front'-type uplift was generated opposite a pinch-point within the orogen. Extensional reactivation of the earlier compressional structures in Permian, and particularly, during Triassic time, resulted in the Worcester Graben as we know it today. The structure of the Malvern Hills and the graben is thus the result of a surprisingly long and complex history of crustal accretion, compression and extension.

Keywords: Malvern Hills; Lineament; Worcester Graben; Proto-graben; River Severn Uplift

Introduction

This review considers the geological history of the triangular region labelled 'River Severn Uplift' in Figure 1 *(overleaf)*, separating the Welsh Massif in the west from the Anglo-Brabant Massif (ABM) to the east (Pharaoh 2018). It comprises a fault-bounded wedge of crust, which exhibits a complex history of crustal accretion, followed by multiple extensional and compressional reactivation. Today it corresponds to the Worcester Graben, with the Malvern Hills defining its western margin, but, as will be described, the Permian-Mesozoic graben is superimposed on a much more fundamental structure. This structure likely extends a significant distance farther south beneath the thin-skinned Variscan parautochthonous thrust nappes (Pharaoh 2018). Careful study of clast composition in Late Carboniferous sandstones and Early Permian breccias in the West Midlands revealed a complex history of fault reversal and reactivation (Wills 1948), and Variscan inversion, long before seismic data were available. In the 1960s, a considerable improvement in palaeogeographical knowledge resulted from coal and hydrocarbon exploration. In the early 1980s, this generated an extensive coverage of 2D seismic reflection data, enabling comprehensive mapping of the Permian and Mesozoic basins of southern Britain (Whittaker *et al.* 1985; Smith *et al.* 2005; Butler 2018).

Crustal structure

The Neoproterozoic basement of southern Britain has been divided into a number of lithotectonic terranes (Pharaoh *et al.* 1987; Pharaoh and Carney 2000). Most of the central part of the ABM is underlain by Ediacaran intermediate and felsic volcaniclastic rocks, comprising the Charnwood Terrane. These crop out in Charnwood Forest, where they are located in a crustal duplex of probable Caledonian age at the north-east margin of the Midlands Microcraton (Fig. 1), and as the Caldecote Volcanic Formation in the Nuneaton area (Carney and Pharaoh 1993; Bridge *et al.* 1998). As described below, the geochemical affinities of basement rocks proved by deep boreholes at Kempsey (in the Worcester Graben), and Withycombe Farm (in Oxfordshire) (Fig. 1) also lie with the Charnian magma type (Pharaoh and Gibbons 1994). From the Malvern Hills westward through the Welsh Borderland, the eastern part of the Welsh Massif is inferred to be underlain by Ediacaran basement of the Wrekin Terrane (Pharaoh and Carney 2000). A suture of late Ediacaran age is inferred to separate the Charnwood and Wrekin terranes along the eastern edge of the Malvern Hills (Pharaoh *et al.* 1987).

Reactivation of this Malvern Line or Lineament has controlled extension and inversion along the western edge of the Worcester Graben throughout Palaeozoic and Mesozoic time (Barclay *et al.* 1997). The Neoproterozoic terranes described above were consolidated into the Avalon Composite Terrane (ACT) or Avalon Superterrane (Gibbons 1990; Pharaoh and Carney 2000) shortly before the Precambrian-Cambrian boundary at 541Ma. This probably took place on the Amazonian margin of Gondwana (Nance and Murphy 1994; Murphy *et al.* 2000; Strachan 2012).

Evidence for the crustal structure of the region is provided by the following geophysical datasets (Figs 2 and 3, *page 37*): 1 Magnetic potential field data; 2 Gravity potential field data; and 3 Seismic reflection data.

Much use has been made of geophysical potential field data (magnetic and gravity potential fields) in the structural interpretation of the concealed basement of southern Britain (e.g. Lee *et al*. 1990, 1991). Magnetic and gravity potential field data acquired by BGS provide a complete regional coverage. The results of interpretation of these data are presented in various BGS memoirs, sub-surface memoirs and geophysical CDs. Two compact magnetic anomalies — 'BMA' (Birmingham Magnetic Anomaly) and 'CEMA' (S Central England Magnetic Anomaly) — have been attributed to the presence of shallow Neoproterozoic (Charnian) metavolcanic rocks (Lee *et al.* 1990; Busby *et al.* 1993). The high

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magnetic susceptibility of the Charnwood Terrane (and CEMA) suggests that the felsic volcanic and volcaniclastic rocks inferred in the upper crust are replaced by more intermediate, magnetite-rich plutonic magmatic rocks at greater depth. West of the Malvern Line, the Wrekin Terrane is also characterised by strong magnetic anomalies, attributed to Uriconian mafic lavas, and, possibly, to plutonic components akin to the Malverns Complex. The region studied has a relatively muted magnetic signature owing to the presence of a thick sedimentary cover, except where the Malverns Complex is exposed or lies at shallow depth ('MMA', Fig. 2). The gravity anomaly map (Fig. 3) reflects the presence of thick Permian to Mesozoic strata in the Worcester Graben, and in the Wessex-Weald Basin to south of the Variscan Front. On both gravity and magnetic images, the N–S trend of the Malvern Line is clearly visible, extending from the mapped Malverns Complex at crop at least as far south as the Variscan Front. The projection of the line to the north, through the basins of the West Midlands, is less clear, but can be tentatively followed at least as far as the Cheshire Basin, and possibly to the Pendle Lineament.

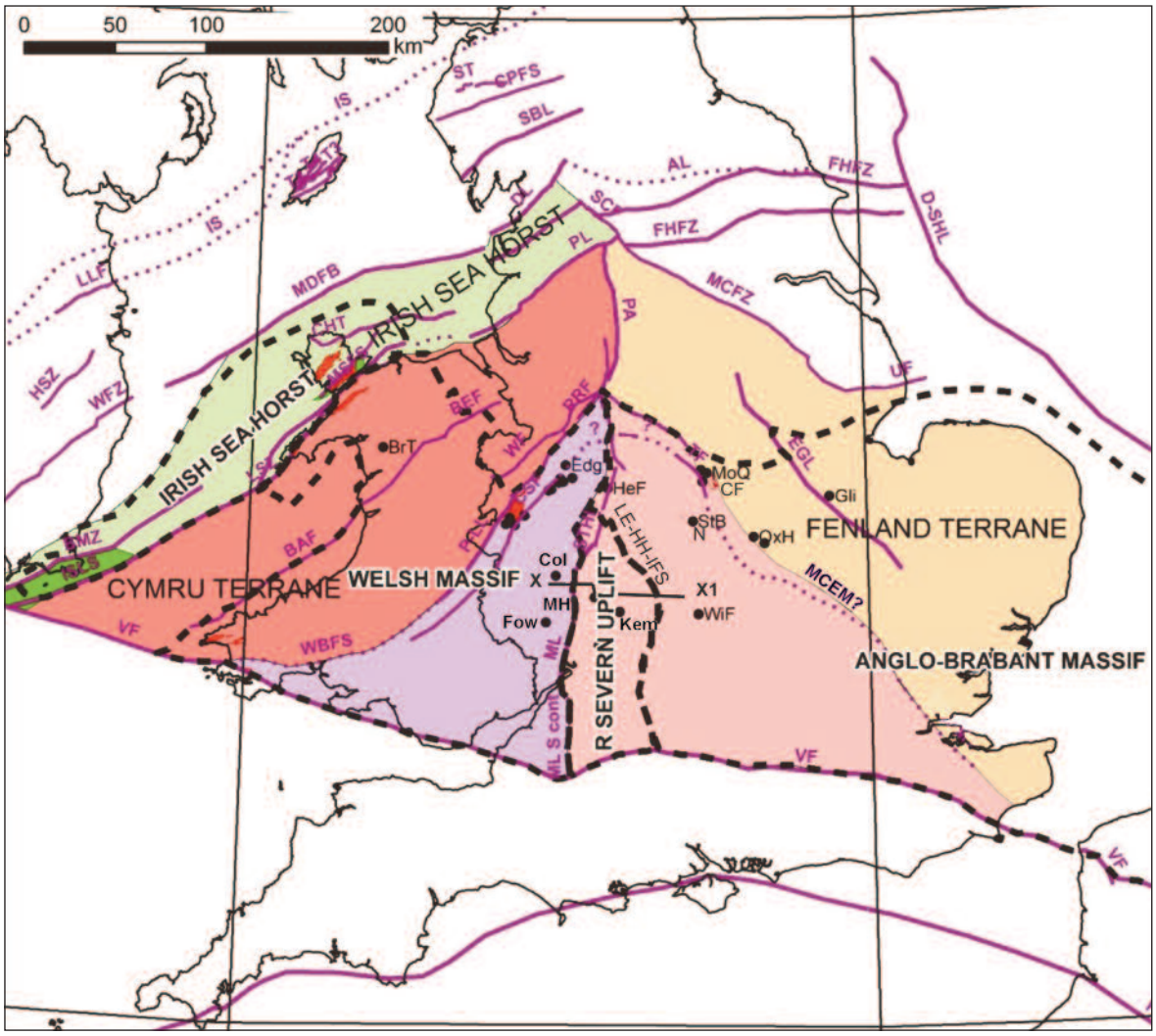
The Worcester Graben and adjacent concealed Oxfordshire-Berkshire Coalfield areas (Butler 2018) are one of the few parts of the ABM with a good seismic coverage conducted in hydrocarbon exploration. In addition, a small number of seismic reflection

Figure 1 Tectonic boundaries of Neoproterozoic crust within the Avalon and Monian composite terranes of central Britain north of the Variscan Front (after Pharaoh and Carney 2000; Pharaoh 2018). Terranes are indicated by different colours; seismic transect X–X1 is depicted in Fig. 4.

Faults and lineaments: AL = Askrigg Line, BAF = Bala Fault, BEF = Bryneglwys Fault, CHT = Carmel Head Thrust, CPFS = Causey Pike Fault System, CSF = Church Stretton Fault Zone, DL = Dent Line, D-SHL = Dowsing-South Hewett Lineament, EGL = Eakring-Glinton Lineament, EVF = Enville Fault, FHFZ = Vale of Pickering-Flamborough Head Fault Zone, LE-HH-IFS = Lickey End-Haselor Hill-Inkberrow Fault System, IS = Iapetus Suture Zone, ISLS = Irish Sea Lineament (South), LEF = Lask Edge Fault, LLF = Lowther Lodge Fault, LSZ = Lŷn Shear Zone, MCEM? = Conjectured Microcraton Eastern Margin, MCFZ = Morley-Campsall Fault Zone, MCWM = Microcraton NW Margin, MDFB = Môn-Deemster Fold-Thrust Belt, ML = Malvern Line, MSFS = Menai Strait Fault System, PA = Pennine Axis, PL = Pendle Lineament, PLL = Pontesford-Linley Fault, RFB = Ribblesdale Foldbelt N margin, RRF = Red Rock Fault, SBL = Southern Borrowdale Lineament, SCF = South Craven Fault, ST = Skiddaw Thrust, TF = Thringstone Fault, UF = Unnamed Fault, VF = Variscan Front, WF = Wem Fault, WBFS = Welsh Borderland Fault System, WFZ = Wicklow Fault Zone.

Solid red ornament—Precambrian outcrop: CF = Charnwood Forest, MH = Malvern Hills, N = Nuneaton.

Dots—boreholes proving Precambrian: BaH = Bardon Hill, BrT = Bryn Teg, Col = Collington 1, Edg = Edgmond 1, Fow = Fownhope 1, Gli = Glinton 1, HeF = Heath Farm 1, Kem = Kempsey 1, MoQ = Morley Quarry, Ort = Orton, OxH = Oxendon Hall, StB = Stretton Baskerville, WiF = Withycombe Farm, Wrb = Wrekin Buildings (Telford 2).



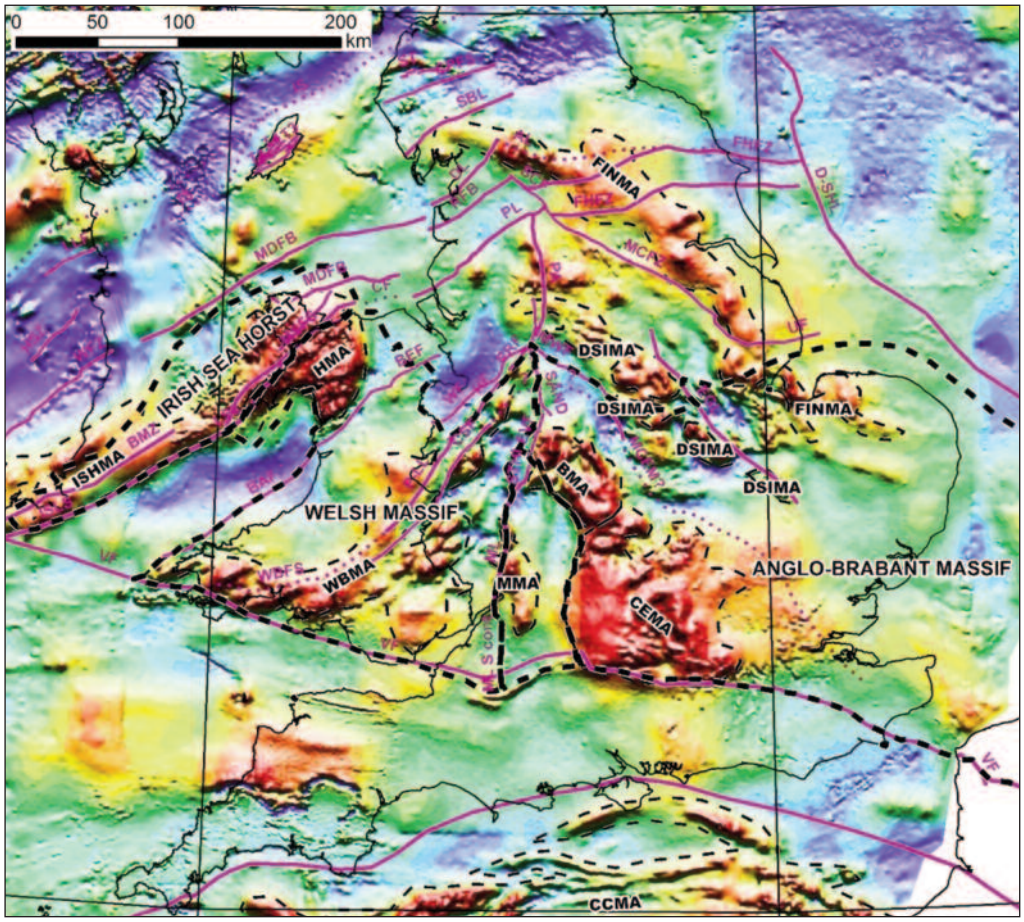


Figure 2 Magnetic potential field: anomaly colour scales range from positive (red) to negative (blue).

Magnetic anomalies described in the text: BMA = Birmingham Magnetic Anomaly, DSIMA = Derby-St Ives Magnetic Anomaly, FINMA = Furness-Ingleton-Norfolk Magnetic Anomaly (after Wills 1978; Pharaoh et al. *1993), CEMA = South Central England Magnetic Anomaly (after Lee* et al. *1990; Busby* et al. *1993), CCMA = Central Channel Magnetic anomalies, HMA = Harlech Magnetic Anomaly, MMA = Malvern Magnetic Anomaly, WBMA = Welsh Borderland Magnetic Anomaly. (For key to major faults and lineaments see Fig. 1.)*

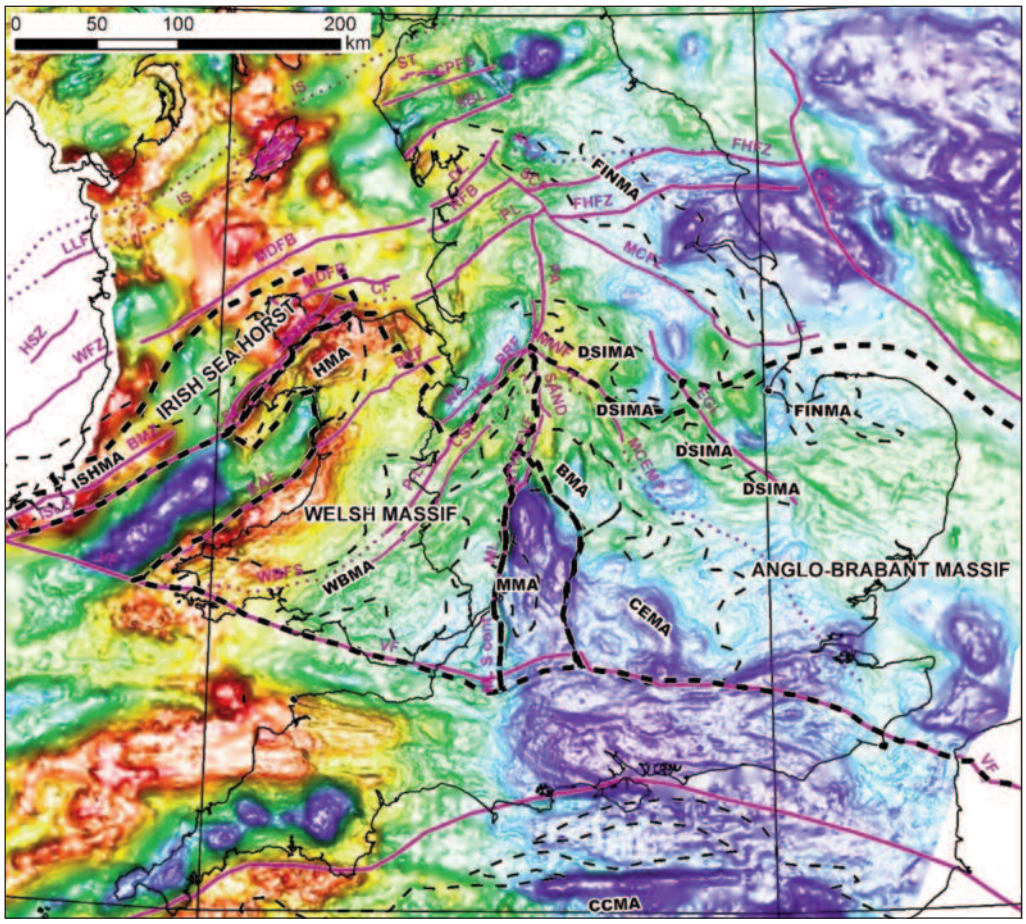
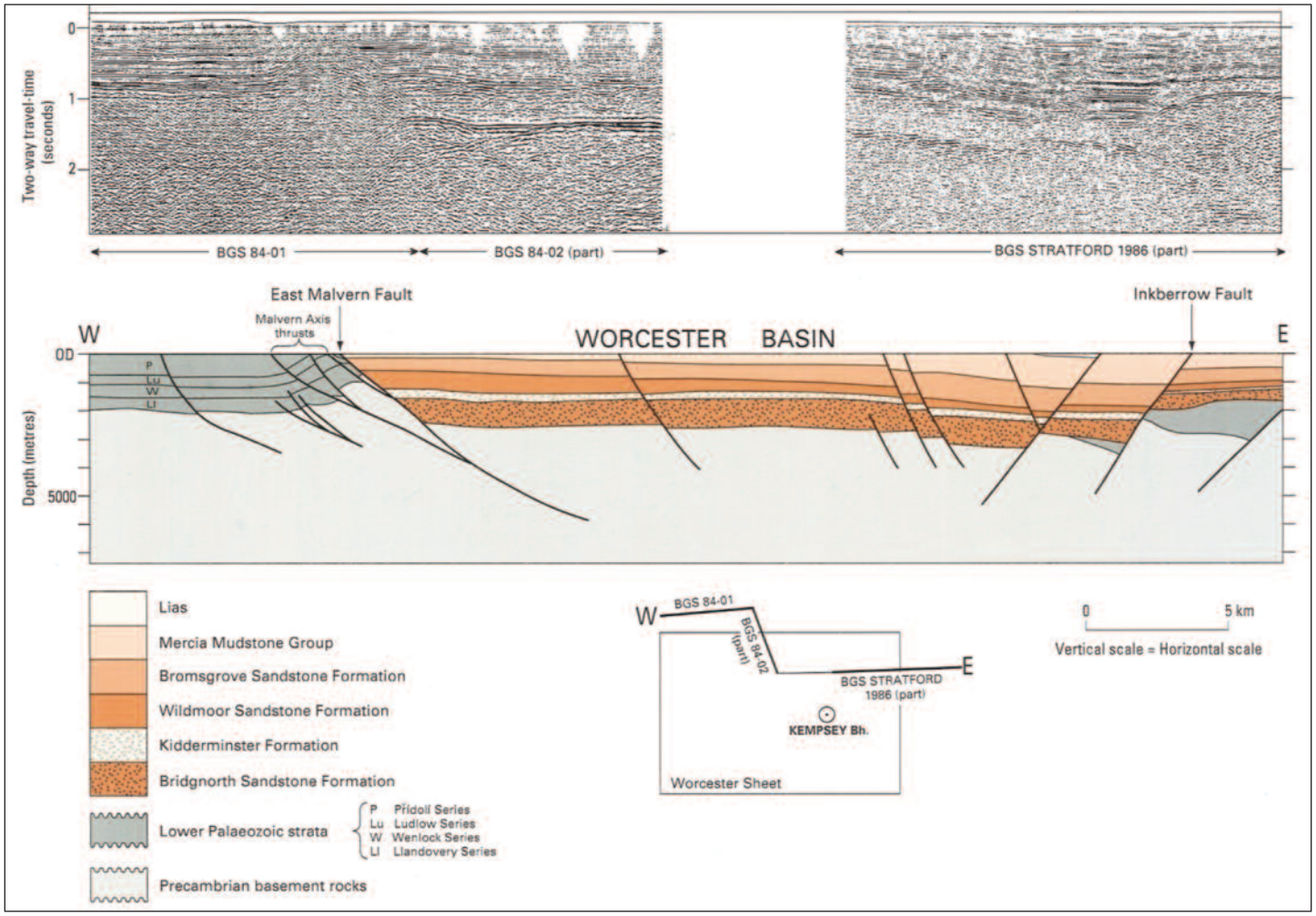
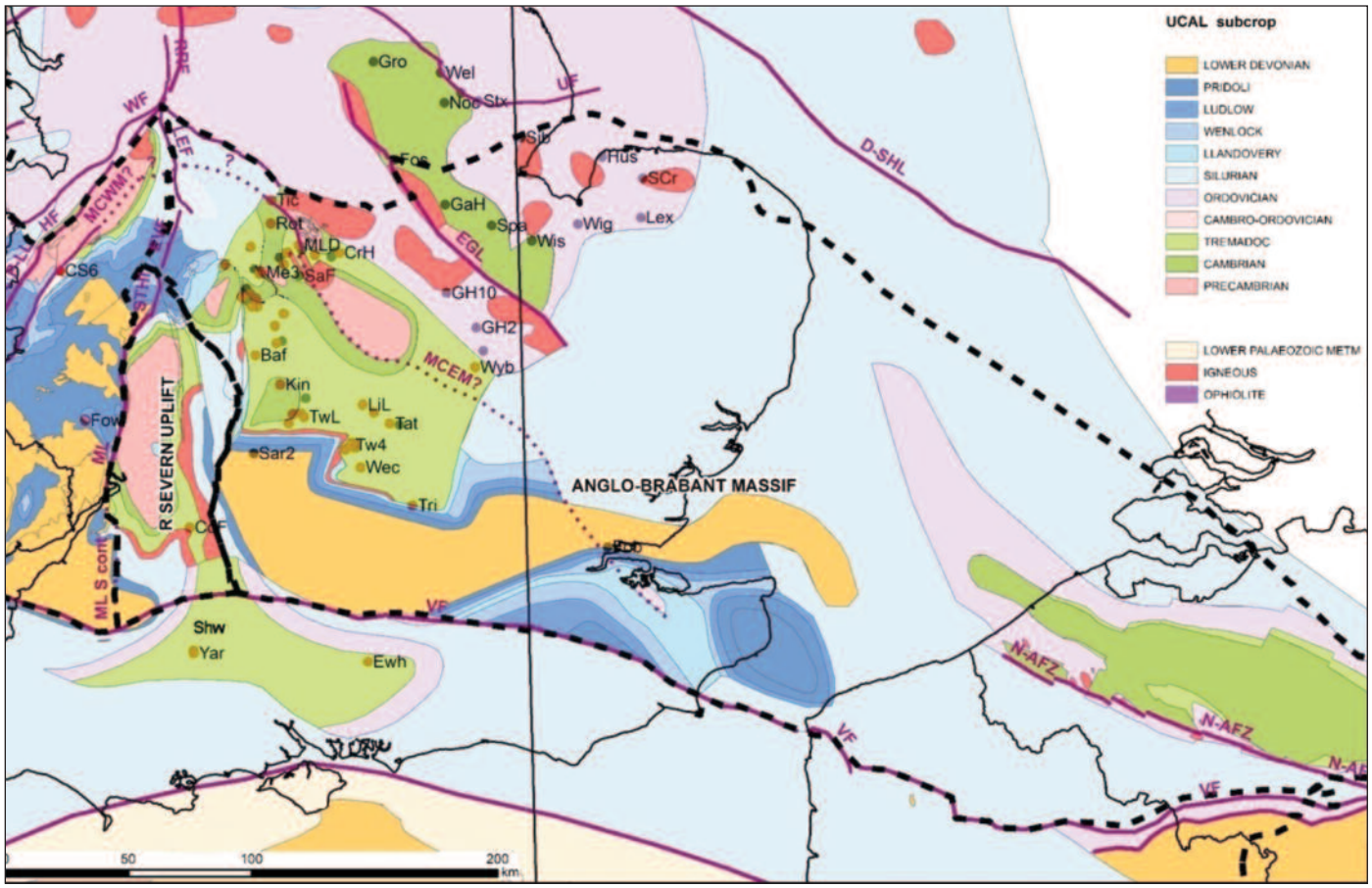


Figure 3 Gravity potential fields, Bouguer anomaly onshore combined with free air anomaly offshore: anomaly colour scales range from positive (red) to negative (blue); magnetic anomalies depicted in Fig. 2 included for reference (for key to major faults and lineaments see Fig. 1).


Two-way travel-time (seconds)
0
1
2
BGS 84-01
BGS 84-02 (part)
BGS STRATFORD 1986 (part)
East Malvern Fault
Malvern Axis thrusts
Inkberrow Fault
W
E
WORCESTER BASIN
OD
5000
Depth (metres)
P
Lu
W
Ll
Lias
Mercia Mudstone Group
Bromsgrove Sandstone Formation
Wildmoor Sandstone Formation
Kidderminster Formation
Bridgnorth Sandstone Formation
Lower Palaeozoic strata
P Přídolí Series
Lu Ludlow Series
W Wenlock Series
Ll Llandovery Series
Precambrian basement rocks
BGS 84-01
BGS 84-02 (part)
BGS STRATFORD 1986 (part)
KEMPSEY Bh.
Worcester Sheet
0
5 km
Vertical scale = Horizontal scale


UCAL subcrop
LOWER DEVONIAN
PRIDOLI
LUDLOW
WENLOCK
LLANDOVERY
SILURIAN
ORDOVICIAN
CAMBRO-ORDOVICIAN
TREMADOC
CAMBRIAN
PRECAMBRIAN
LOWER PALAEOZOIC METM
IGNEOUS
OPHIOLITE
ANGLO-BRABANT MASSIF
R SEVERN UPLIFT
D-SHL
MCEM?
EGL
N-AFZ
VF
WF
HF
MCWM?
EEF
UF
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Me3
SaF
CS6
GH10
GH2
Wyb
Baf
Kin
TwL
LiL
Tat
Tw4
Wec
Sar2
Tri
Fow
Shw
Yar
Ewh
50
100
200
km

Figure 4 E–W (previous page, top) seismic transect across the Worcester Basin and its margins (reproduced from Barclay et al. *1997). Location shown on Fig. 1. Based on seismic reflection data acquired by BGS (Chadwick 1985; Chadwick and Smith 1988; Chadwick and Evans 2005).*

profiles gathered by the British Geological Survey provides significant insights to crustal structure in this region (Chadwick 1985; Chadwick and Smith 1988). Figure 4 *(previous page)* displays reflection seismic data and their interpretation, forming an E–W transect across the Worcester Graben. Some 2.5–3km of Permian, Triassic and Early Jurassic strata fill the graben, the floor of which has a complex subcrop (Fig. 5, *previous page*). Over a large area, Precambrian rocks of the Kempsey Formation are inferred to subcrop (Barclay *et al.* 1997). These are overlain by a Cambrian-Tremadocian sequence, which thickens southward, and by a thin Silurian sequence, including volcanic rocks. Devonian and Carboniferous strata are absent except in the north, in the basins associated with the northern edge of the ABM. In contrast, relatively thick Devonian-Pennsylvanian sequences are found both west of the Malvern Line, in the West Midlands basins; and to the east, in the concealed Oxfordshire-Berkshire Coalfield. The inference is that the Malvern region was strongly inverted after deposition of Pennsylvanian strata, i.e. by the Variscan Orogeny (Chadwick and Smith 1988; Peace and Besly 1997); and that an earlier phase of graben development controlled Cambrian to Tremadocian sedimentation (Smith 1987; Smith and Rushton 1993).

The evidence reviewed here indicates that multiple reactivation of the Malvern crustal suture has occurred, both in extension (late Cambrian-Tremadocian, Triassic) and in compression (?Arenig, ?Early Devonian, late Pennsylvanian). It shows that the crust beneath the Malvern Hills and Worcester Graben is significantly weaker than that of the Welsh Massif and the ABM (Pharaoh 2018). Recently, Smit *et al.* (2018) invoked the Malvern Line as the boundary between their western and central crustal domains. They advocate up to 15° of anti-clockwise rotation of the Brabant Massif with respect to the Welsh Massif, along an arc-shaped Malvern Line, to accommodate Mississippian extension in eastern England and the southern North Sea. Published mapping of the Malvern region, and its subsurface continuation to the south, inferred from geophysical and subsurface geological evidence (as reviewed here), indicate that the Malvern Line has a linear N–S trend, which is not arc-shaped or curvilinear, as required by this model (Fig. 6).

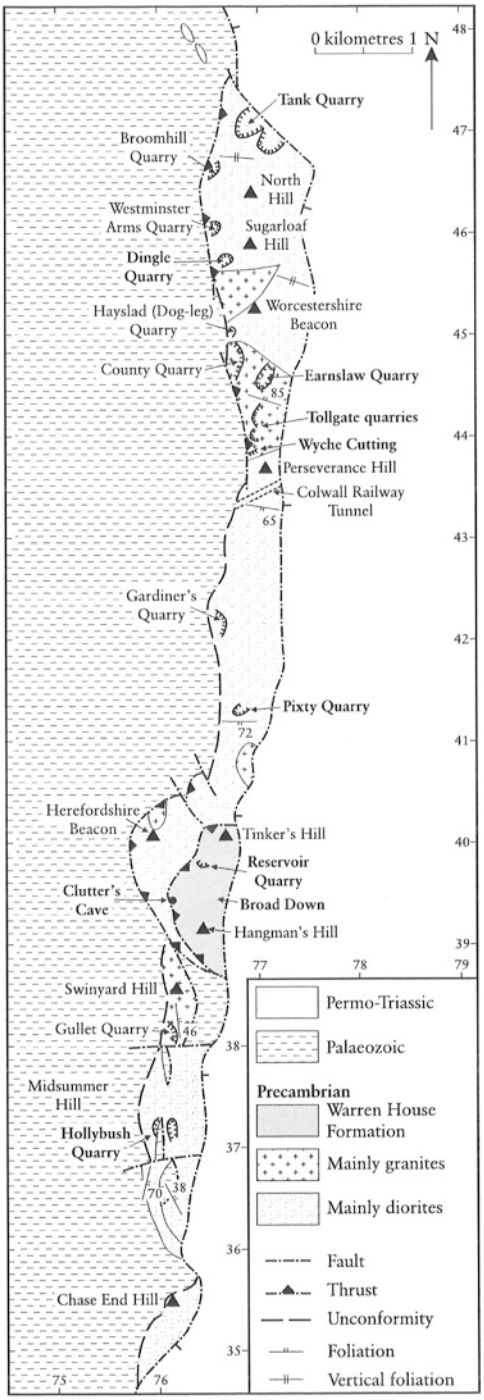


Figure 6 Simplified geological map of the Malvern Hills (after Lambert and Holland 1971; Barclay et al. *1997; Barclay and Pharaoh 2000).*

Precambrian evolution

The oldest known magmatic rocks in England and Wales are the Stanner-Hanter Complex, a bimodal gabbro-granite suite, crystallised at *c.* 711Ma (Schofield *et al.* 2010). Slightly younger U-Pb ages have been obtained from the Malverns Complex, involved in a transpressional flower structure of Variscan age on the western side of the Worcester Graben (Fig. 1). The strong

Figure 5 (previous page, bottom) Cambrian-Tremadocian outcrop and borehole provings in southern Britain (base map for UK from unpublished mapping of the Acadian Unconformity by Nigel Smith). For key to major faults and lineaments see Fig. 1.

Outcrop (solid ornament) borehole provings:

Early to middle Cambrian (black): Fob = Fobbing, SaF = Sapcote Freeholt (Elmesthorpe), Fow = Fownhope 1, Kin = Kineton, Me3 = Merevale No. 3, MoF = Moor Farm, Rot = Rotherwood, Tic = Ticknall (Calke Abbey), WiF = Withycombe Farm.

Possible Cambrian provings: Bay = Bardney 1, GH2 = Ellington, Fos = Foston 1, GaH = Galley Hill, Gro = Grove 3, Hus = Hunstanton 1, Gh10 = Huntingdon 10, GH5 = Huntingdon 5, Lex = Lexham 1, Noc = Nocton 1, Sib = Sibsey 1, SCr = South Creake 1, Spa = Spalding 1, Stx = Stixwould 1, Wel = Welton 1, Wes = Wessenden 1, Wig = Wiggenhall 1, Wis = Wisbech 1, Cof = Cooles Farm 1 (Minety).

Tremadocian provings (red): Baf = Barford, CaW = Calvert (West), Cof = Cooles Farm 1 (Minety), CrH = Crown Hills (Evington), Dad = Dadlington, EWh = East Worldham 1, Fow = Fownhope 1, GaF = Gables Farm, HoB = Hollies Barn, LFE = Leicester Forest East, LiL = Lillingstone Lovell, Me2 = Merevale No. 2, Mer = Meriden, Shw = Shrewton, Tat = Tattenhoe, Tri = Tring (Superior), Tw4 = Twyford 4, Wec = Westcott No. 1, Wyb = Wyboston, Yar = Yarnbury.

calk-akaline signature in mafic and intermediate compositions (Fig. 7) is more reliably confirmed by the Mid-Ocean Ridge Basalt (MORB)-normalised geochemical patterns, which show strong enrichment in large ion lithophile elements (LILE) such as Th and Rb, and by light rare earth elements (LREE) such as Ce, and depletion of high field strength elements (HFSE) such as Nb and Ti (Fig. 8). Granitoid components of the calc-alkaline intrusive complex have been reliably dated to 677±2Ma (Tucker and Pharaoh 1991) using the U-Pb zircon method. A volumetrically smaller component of paragneiss, interpreted as a host to the plutonic rocks, yields zircons with core U-Pb ages as old as 1965±7Ma, with significant concentrations at 1.6 to 1.5Ga, and 1.3 to 1.0Ga (Strachan *et al.* 2007). The complex was subjected to metamorphism at greenschist to amphibolite facies between 670 and 650Ma (Strachan *et al.* 1996). Mesoproterozoic zircon inheritance is present in both Malvern and Stanner-Hanter complexes (Tucker and Pharaoh 1991; Strachan *et al.* 2007; Schofield *et al.* 2010). This is supported by Sm-Nd model ages, and favours an origin in the Gondwanan part of Rodinia closest to the Amazon Craton and Mexico (Nance and Murphy 1994; Strachan *et al.* 2007) rather than in the West African Craton, where such rocks are absent. Detrital zircon suites from early Cambrian quartz arenites also support this conclusion (Murphy *et al.* 2004).

Lavas of the Warren House Formation form a small (<1 km^2) outcrop (Fig. 6) on the eastern flank of the Malvern Hills (Penn and French 1971; Thorpe 1974). Altered basalt and basaltic andesite lavas, exhibiting small pillow structures, occur with minor amounts of rhyolitic tuff, the latter yielding concordant U-Pb zircon ages of 566±2Ma (Tucker and Pharaoh 1991). These rocks are at much lower metamorphic grade than the Malverns Complex, with which they were tectonically juxtaposed during Variscan thrusting (Barclay *et al.* 1997). Despite their insignificant outcrop area, the Warren House Formation lavas provide important evidence of a late Proterozoic suture between the Wrekin and Charnwood terranes. Although identical in age to the Uriconian lavas (Tucker and Pharaoh 1991), the geochemical composition of basaltic components differs. The Uriconian basalts have a significant subduction-related component (enrichment of LILE, LREE etc; Fig. 9, *opposite*); the Warren House basalts have a smaller subduction component and are chemically most similar to primitive marginal basin basalts (Thorpe 1972, 1974; Pharaoh *et al.* 1987). The Warren House basalts show comparable depletion in HFSE (such as Nb, Ta, Ti and Y) to Kempsey Formation tuffs proved by the Kempsey Borehole (Fig. 10a, b, *opposite*) in the Worcester Graben (Fig. 1), and to more mafic components of the Charnian suite (Fig. 10c). Thus, rocks of Charnian magmatic affinity (and the Charnwood Terrane) are inferred to underlie the Worcester Graben, and extend to the Malvern Line.

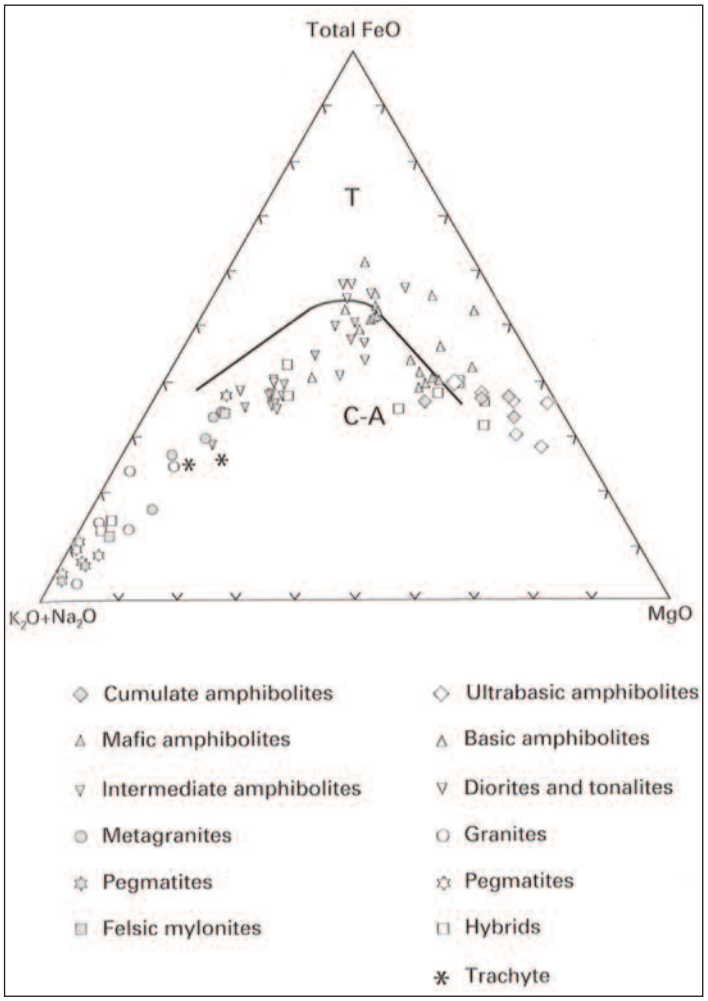


Figure 7 (above right) AFM diagram for samples of the Malverns Complex: boundary between tholeiitic (T) and calc-alkaline (C-A) fields (after Irvine and Barager 1971; reproduced from Barclay et al. *1997).*

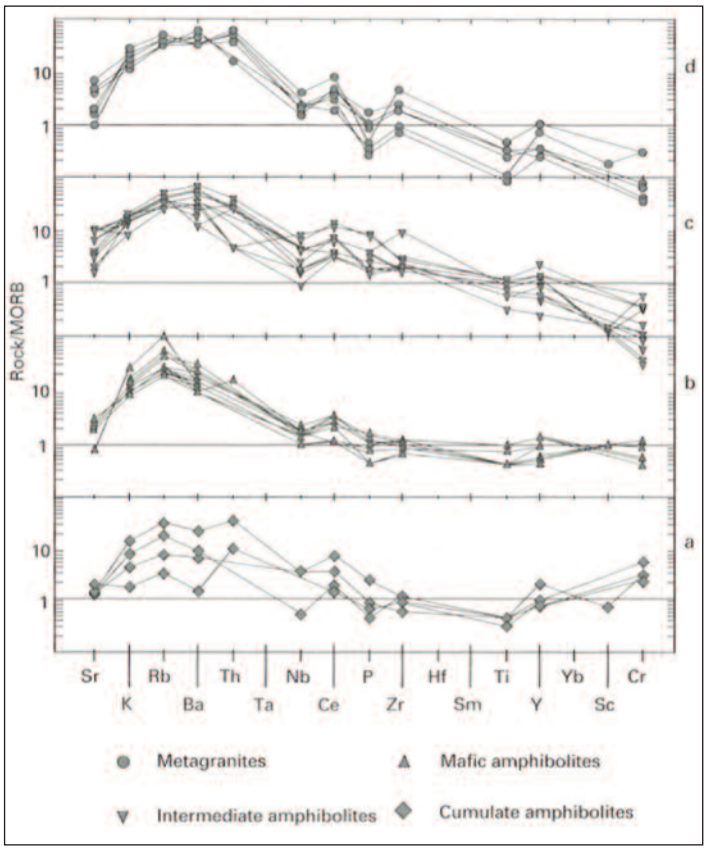


Figure 8 (right) Geochemical patterns for components of the Malverns Complex, with MORB-normalised values (after Pearce 1982; reproduced from Barclay et al. *1997): a = Cumulate ultramafic and mafic amphibolites, b = Non-cumulate mafic amphibolites, c = Amphibolites of dioritic and tonalitic composition, d = Metagranitic rocks.*

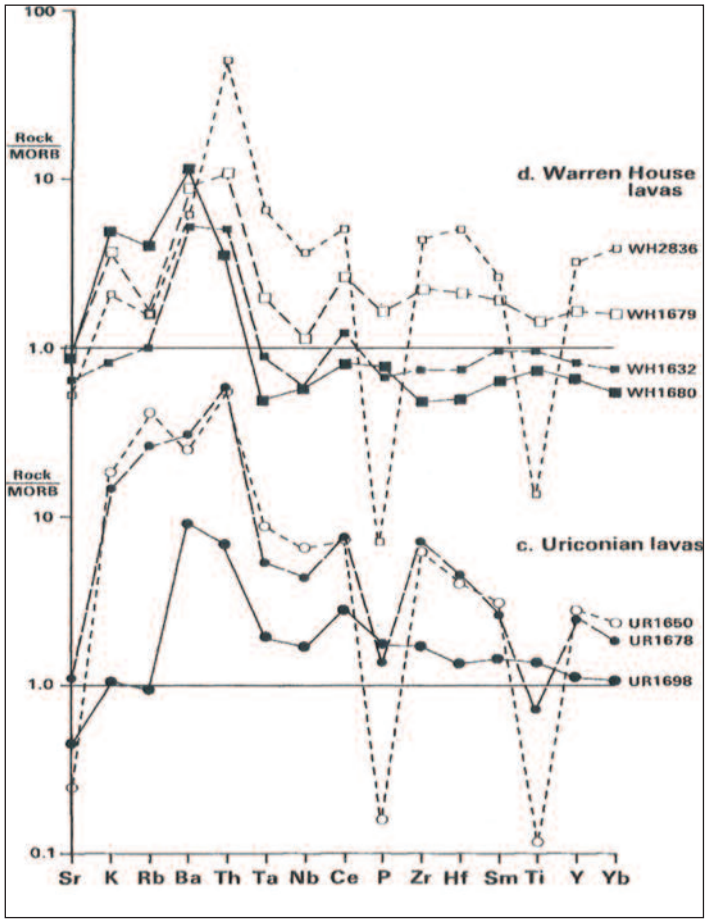


Figure 9 (above) Geochemical patterns for late Neoproterozoic metavolcanics suites, with MORB-normalised values after (Pearce 1982; reproduced from Barclay et al. *1997): a = Uriconian volcanic group lavas, b = Warren House Formation lavas, solid symbol = mafic compositions, open symbol = felsic compositions.*

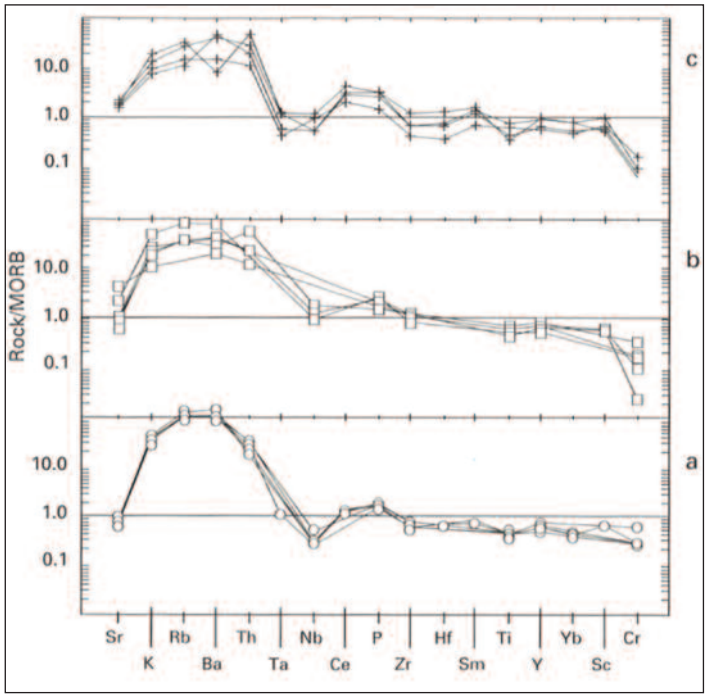


Figure 10 (below left) Geochemical patterns for components of the Kempsey Formation and microdioritic Charnwood magma types, with MORB-normalised values (after Pearce 1982; reproduced from Barclay et al. *1997): a = Clasts of intermediate tuff from core samples of the Kempsey Formation, b = Tuffaceous matrix to clasts and lithic sandstones from core samples of the Kempsey Formation, c = Diorites from the Charnwood area, representative of the Charnian magma type (after Pharaoh* et al. *1987).*

Early Palaeozoic evolution

Brief erosion of the juvenile Neoproterozoic crust preceded a significant marine transgression onto the margin of Gondwana (Brasier and Hewitt 1979), generally presumed to be by the Iapetus Ocean, which began opening in latest Neoproterozoic time, breaking up the supercontinent of Rodinia-Pannotia (Dalziel 1997). That part of the Avalon Composite Terrane (Pharaoh and Carney 2000) comprising the Wrekin and Charnwood terranes (including this region) formed the shallow marine Midland Platform (e.g. Cope *et al.* 1992; Woodcock 2012a). An overstepping cover sequence comprising thin (30–60m) basal shoreface quartz arenitic facies, e.g. the Malvern and Wrekin quartzites, passes up into 200–300m thick nearshore clastics (e.g. the Hollybush Sandstone Formation) (Brasier *et al.* 1978; Woodcock 2012a). This sequence locally contains 'small shelly fossil' horizons comprising hyoliths and primitive molluscs (Brasier 1984) that can be precisely correlated with strata of the upper Terreneuvian Series in the Avalon Peninsula of southeast Newfoundland (Brasier 1992). The same assemblage is found overlying lavas with Charnian magmatic affinity in the Withycombe Farm Borehole in the concealed Oxfordshire-Berkshire Coalfield (Rushton and Molyneux 1990; Pharaoh and Gibbons 1994; Rushton *et al.* 2011) (Fig. 11, *overleaf*). The oldest Cambrian (Fortunian) stage is missing, so a time gap of perhaps 15Ma exists from the start of the period at 541Ma. Overlying strata are mid- to late-Cambrian (International epochs 2, 3 and Furongian) mudstones with subordinate sandstones and/or limestones, deposited below wave-base on a gently subsiding shelf. Numerous boreholes drilled for exploration of the concealed Warwickshire Coalfield (Fig. 11), east of the Worcester Graben terminate in Cambrian or earliest Ordovician (Tremadocian) strata (Worssam and Old 1988; Bridge *et al.* 1998). For clarity, not all of the boreholes are labelled in Figure 5, which gives a general impression of their distribution. Most cores are of Furongian age (Rushton *et al.* 2011). The presence of dips up to 60° in many of these boreholes demonstrates that the sequence is strongly folded across a wide area.

Smith and Rushton (1993) recognised that the Worcester Graben, presently filled with Permo-Triassic strata, had an early Palaeozoic antecedent, referred to as the 'Tremadoc Worcester Graben', and here as the 'Worcester Proto-graben'. This major N–S trending structure probably initiated as an 'aulacogen' (Hoffman *et al.* 1974), possibly the 'failed arm' of a continental margin rift prior to opening of the Rheic Ocean. The increasing width of the proto-graben to the south indicates that the margin lay in that direction, reflected in thickening of the Tremadocian strata (to > 2km) at crop in the Tortworth Inlier, and in boreholes (Fig. 5) at Cooles Farm, and at Yarnbury and Shrewton south of the Variscan Front (Smith and Rushton 1993). Subsidence of this

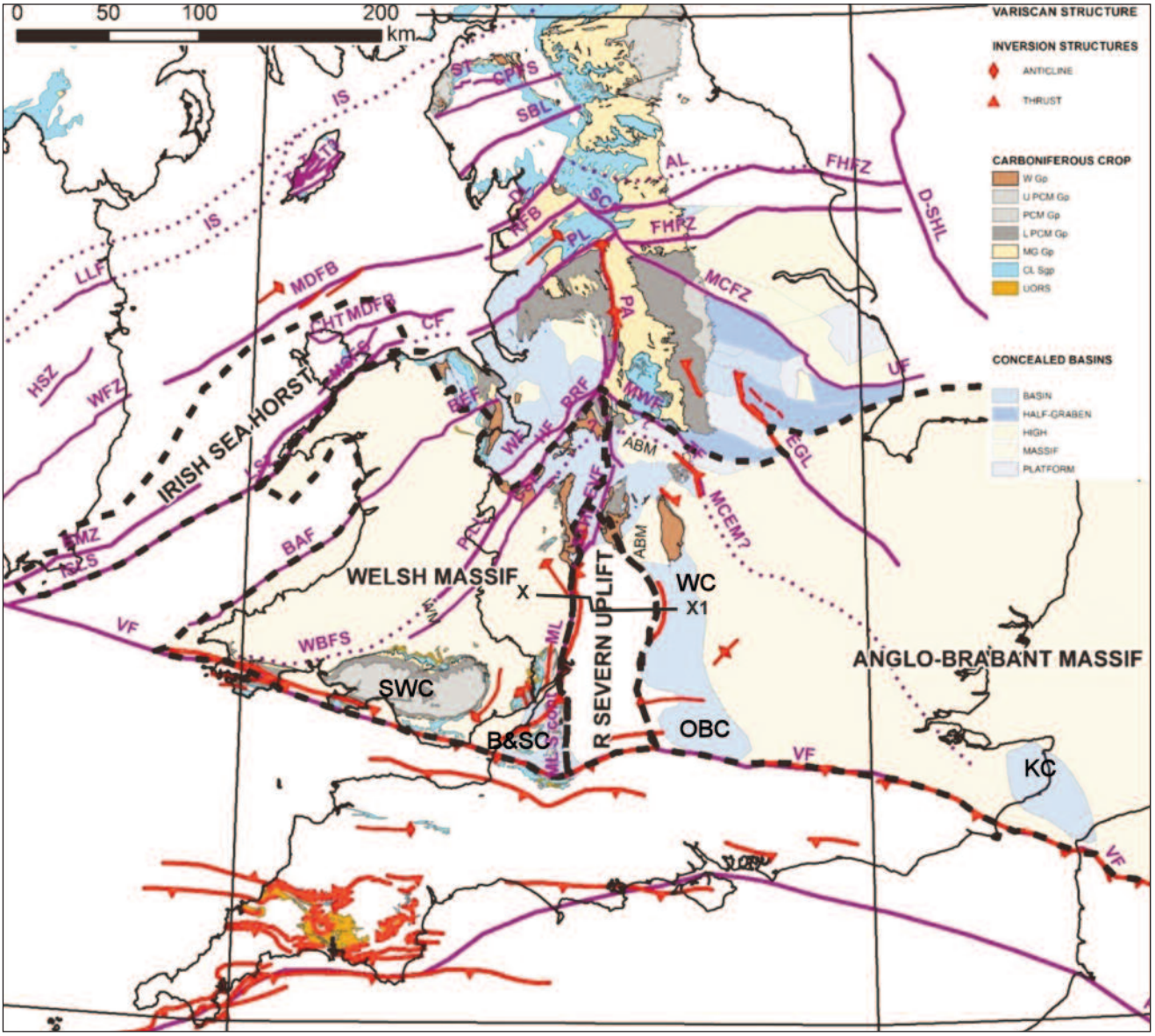


Figure 11 Variscan inversion structures surrounding the ABM (exposed geology after BGS 1:625000 digital mapping; concealed basins after BGS 1999 and Pharaoh et al. *2011; Variscan structures after BGS 1996). (For key to major faults and lineaments see Fig. 1.): UORS = Upper Old Red Sandstone (Upper Devonian), CL Sgp = Carboniferous Limestone Supergroup (Visean-Tournaisian), MG Gp = Millstone Grit Group (Namurian), L PCM Gp = Lower Pennine Coal Measures Group (Westphalian A), U PCM Gp = Upper Pennine Coal Measures Group (Westphalian B/C), W Gp = Warwickshire Group (Westphalian C/D); concealed Carboniferous basins (shades of blue): B&SC = Bristol & Somerset Coalfield, KC = Kent Coalfield, OBC = concealed Oxfordshire-Berkshire Coalfield, WC = Warwickshire Coalfield, SWC = S Wales Coalfield.*

N–S trending proto-graben followed reactivation of the Neoproterozoic Malvern Line suture in extension. This anticipated the break-off of a microcontinent from the peri-Gondwana margin, subsequently known as Avalonia. Post-Tremadocian Ordovician strata are not preserved on the platform, so its subsequent subsidence history is not known, unlike the basin (Prigmore *et al.* 1997).

The consensus view is that the faunally-defined Avalonia microcontinent rifted away from Gondwana at high southerly palaeolatitude in late Early Ordovician (Floian) time (Scotese and McKerrow 1991; Prigmore *et al.* 1997; Fortey and Cocks 2003; Cocks and Torsvik 2006; Woodcock 2012b). As it drifted northward, a new (Rheic) ocean basin opened in its wake; and the old (Iapetus) ocean crust was destroyed by subduction zones on both its Laurentian and Avalonian margins. Part of this Iapetus Ocean, referred to as the Tornquist Sea by Cocks and Fortey (1982), lay between Avalonia and Baltica. Faunal contrast with Gondwana only became apparent in Darriwilian (late Llanvirn) time (Woodcock 2012b). On the Avalonian margin, the earliest subduction magmatism is of late Tremadocian age at Treffgarne and Rhobell in the Welsh Basin (Kokelaar 1986, 1988).

Numerous small intrusions belonging to the lamprophyric-microdioritic Midlands Minor Intrusive Suite are encountered in exposed Cambrian-Tremadocian strata (e.g. Malverns, Wrekin, Nuneaton) and numerous boreholes throughout the microcraton (Carney *et al.* 1992; Thorpe *et al.* 1993; Pharaoh *et al.* 1993). They are not observed to intrude Silurian strata, however, as noted by Wills (1948) (Fig. 3). These geological observations are compatible with the U-Pb baddeleyite age of 442±3Ma (earliest Silurian) for a differentiated sill in the Mancetter area near

Nuneaton (Noble *et al.* 1993). Field observations indicate that the minor intrusions were emplaced in a number of co-magmatic pulses (Le Bas 1968; Thorpe *et al.* 1993). In some places, dykes cut the axial planes of chevron folds of bedding in Cambrian-Tremadocian strata. A post-Tremadocian/pre-Silurian age is therefore inferred for this deformation (Carney *et al.* 1992; Bridge *et al.* 1998), for which a Penobscotian cause (Waldron *et al.* 2011; Woodcock 2012b) is therefore conceivable. The mineralogical and geochemical composition of these minor intrusions indicates formation by small degrees of partial melting of lithospheric mantle with subduction enrichment of volatiles, LILE and light REE. A within-plate mantle source also provided a contribution. The Midlands Minor Intrusive Suite and comparable lavas in North Wales have been interpreted to reflect the shutdown of volcanism (and subduction) at the northern edge of Avalonia (Woodcock 2012b).

Subsequently, a Silurian shelf sequence was deposited, generally unconformable upon the Precambrian basement (e.g. in the Heath Farm and Collington boreholes). Upper Cambrian-Tremadocian strata are present in the Fownhope Borehole within the Woolhope Basin (Barron and Molyneux 1992), and in the Usk Borehole (Sovereign plc well completion report). A number of minor basins controlled by syndepositional faults developed here (Butler *et al.* 1997), perhaps reflecting stronger extension in the region of the microcraton marginal to the developing Welsh Silurian basin, and associated with the volcanism described in the next section.

Silurian strata containing eruptive volcanic units out-crop at Skomer in south-west Wales (mid-Llandovery), at Tortworth in Gloucestershire (upper Llandovery), and in the Mendips (mid-Wenlock) (Van der Kamp 1969; Thorpe *et al.* 1989); lavas of Llandovery age are also encountered in boreholes at Maesteg in south Wales, at Netherton in the Worcester Graben and at Bicester in Oxfordshire (Pharaoh *et al.* 1991) The lavas form a reflective marker horizon on reflection seismic lines and can be mapped between the borehole provings. All of the volcanic centres are located within *c.* 50km of the Variscan Front, anticipating the subsequent development of the Variscides (Turner 1935; Pharaoh *et al.* 1991, 1993; Fortey *et al.* 1996). In addition, thin ash (bentonite) horizons are more widely distributed both spatially and temporally (Fortey *et al.* 1996), but might not necessarily have been derived from the same volcanic centres (Woodcock 2012c). The chemical composition of the lavas varies from basalt through basaltic-andesite to minor amounts of rhyolite, with both within-plate and subduction magmatic signatures (Thorpe *et al.* 1989; Pharaoh *et al.* 1991). Distinct peralkaline and ocean island basalt series are recognised at Skomer (Thorpe *et al.* 1989), whereas the Mendip and Tortworth occurrences have calc-alkaline affinities (Van der Kamp 1969). This could reflect development of an extensional rift zone on the northern margin of the Rheic Ocean, with a lithosphere previously contaminated by Avalonian or Iapetan subduction (Pharaoh *et al.* 1991); by subduction of the Rheic Ocean northward under the Avalonia plate, following a polarity switch (Fortey *et al.* 1996; Woodcock 2012c); or, given the variety of magmatic series, by a post-subduction sequence recording slab break-off. The third hypothesis presently looks the most reasonable, given that the faunal evidence appears to favour opening of the Rheic Ocean from Floian time onwards (and perhaps earlier) (Scotese and McKerrow 1991; Fortey and Cocks 2003) some 30Ma to 40Ma earlier than the Skomer volcanism. As noted above, in Brabant, magmatism continuing until 433Ma (Early Silurian time) might also be associated with a polarity switch to northward subduction of the Rheic Ocean (Linnemann *et al.* 2012).

Closure of the Rheic Ocean basin, with impingement of the Armorican or Iberian microcontinents upon Avalonia, was invoked by Soper *et al.* (1987) as the cause of the late Caledonian Acadian Orogeny. The Mid-Devonian Acadian Phase is contemporaneous with the Ligerian or 'Eo-Variscan' Phase recognised throughout the Variscides (Ziegler 1990; Matte 2001). High-pressure metamorphism of this age is identified in numerous Variscan Massifs — for example in north-west Iberia, in southern Armorica and in Bohemia (Lardeaux *et al.* 2014) — and reflects collision and obduction of continental terranes in an early ('Eo-Variscan') phase of the Variscan Orogeny. It seems likely that Avalonia was involved in these collisions, albeit peripherally. However, as Woodcock *et al.* (2007) have pointed out, much of the critical evidence for orogeny at this time (e.g. compressional deformation and subduction magmatism) is absent in Cornubia (Devon and Cornwall), the intervening region where it should be present. To resolve these difficulties, Woodcock *et al.* (2007) and Woodcock (2012d) envisaged displacement of the arc/forearc system on the northern Rheic margin by *c*. 400km of dextral shear along a putative Bristol Channel-Bray Fault Zone, the presence of which had already been advocated by Holder and Leveridge (1986). The hypothesis proposes that the crust of what is now Cornubia originated in what is now the western side of the Paris Basin, and was translated to its present position in post-Acadian or early Variscan time, possibly during the Late Carboniferous (Woodcock 2012d). Further discussion of this interesting topic is outside the scope of this review.

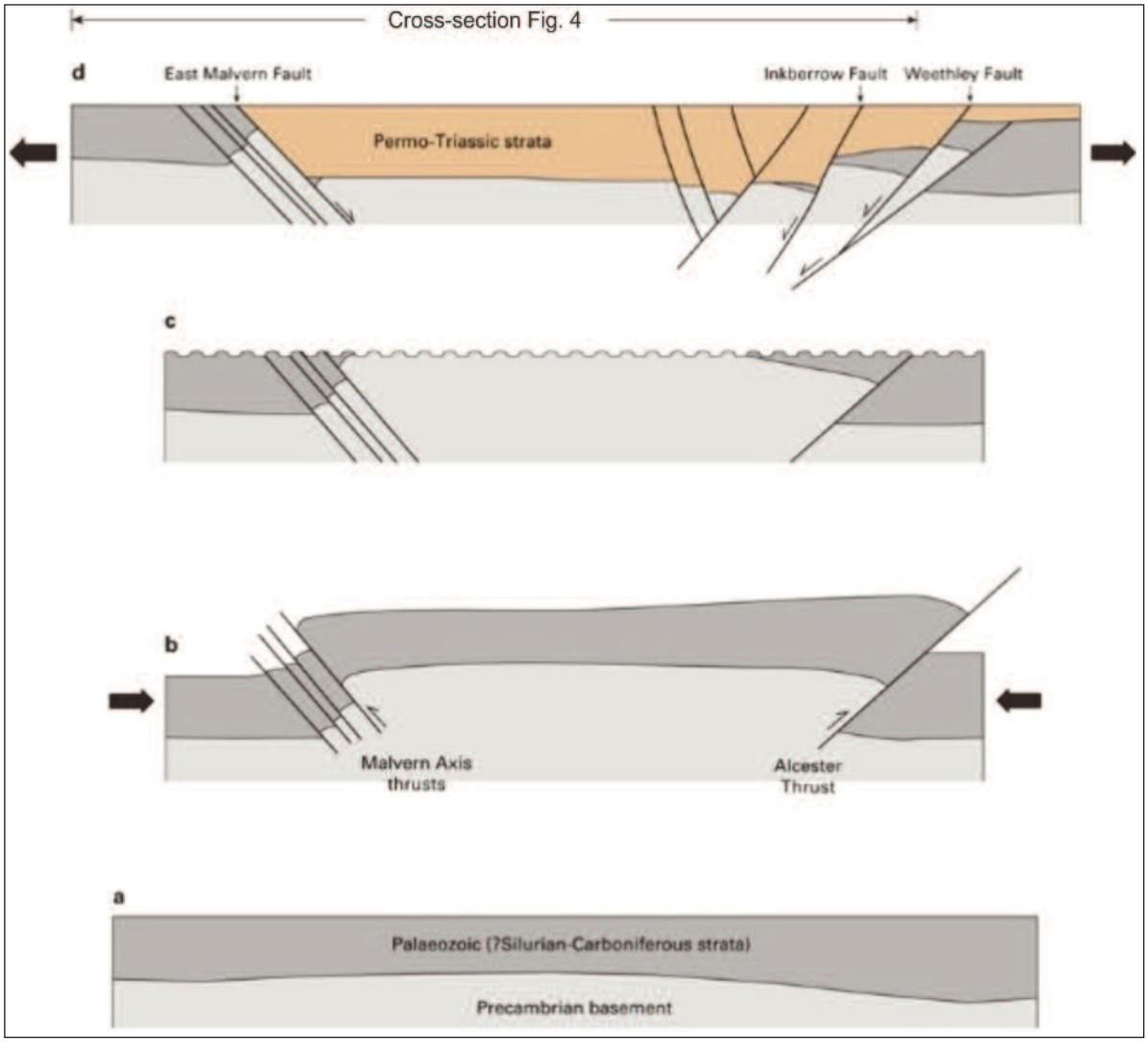
Late Palaeozoic evolution

By Early Devonian time, the accretionary collage of the Caledonide Orogen had been welded into a mountain belt, part of the supercontinent known as 'Laurussia', or the 'Old Red Continent' (Ziegler 1990). Orogen-wide sinistral transtension is most obviously expressed in major fault zones such as the Great Glen and Highland Boundary fault systems, and associated with voluminous granite magmatism (Dewey and Strachan 2003; Soper and Woodcock 2003). Early Devonian strata are absent in the floor of the Worcester Graben. They were probably deposited here, but eroded following severe Variscan inversion along the axis of the Tremadocian proto-graben, for considerable thicknesses (up to 2,500m) of such strata are preserved in South Wales and along the Welsh Borders to west of the Malvern Line, and in a E–W orientated synclinal basin underlying the Thames Valley, extending from Gloucestershire to east Kent (Mortimer and Chaloner 1972; Ellison *et al.* 2004). The proto-graben received the attenuated late Palaeozoic sequence typical of a location within the ABM: thin onlapping sequences of upper Devonian strata; Mississippian strata usually absent; and onlapping late Pennsylvanian strata of the Upper Pennine Coal Measure and Warwickshire groups (Foster *et al.* 1979). The proto-graben possibly escaped inversion in the Acadian phase, but during Late Carboniferous (?Stephanian time), it was inverted as a positive flower structure/horst (Chadwick and Smith 1988), with thrusting westwards at the Malvern Line and eastwards into the Oxford Basin (Peace and Besly 1997). Neoproterozoic volcaniclastic rocks were unroofed at Kempsey in the northern, most squeezed, part of the proto-graben.

By Early Carboniferous time, a regime of N–S extension had become established, possibly resulting from back-arc extension in the hinterland of volcanic arcs established on the southern margin of Laurussia (Leeder 1982; Franke *et al.* 2017). Three major pulses of rapid extension and subsidence have been observed in the Mississippian strata of the Carboniferous Limestone Supergroup deposited across a wide, equatorial platform in northern Wales and northern England (Gawthorpe *et al.* 1989; Fraser *et al.* 1990). On the margins of the ABM, major discontinuities such as angular unconformities, palaeosols and karstified surfaces testify to uplift and emergence (Walkden and Davies 1983; Bridges and Chapman 1988; Ambrose and Carney 1997). It is likely that any Mississippian strata deposited in the region would have been thin, marginal sequences, eroded during early phases of Variscan uplift.

In late Pennsylvanian time, intra-plate stress from the developing Variscan Orogen of central Europe began to impact on the British area. Flexural subsidence on a lithospheric scale resulted in downwarping of the crust and development of a foreland basin along the southern margin of the ABM (Besly and Kelling 1988), initially reflected in minor sequence discordances. These processes resulted in the accumulation of thick late Westphalian to earliest Stephanian 'Barren' and 'Pennant' Coal Measures in Kent, across Oxfordshire–Berkshire (Foster *et al.* 1979) and in South Wales (*see* Fig. 11). The crust of the British area responded to N–S Variscan shortening in a strongly heterogeneous fashion (Corfield *et al.* 1996), typically by compressional reactivation of the original extensional faults. In the wider orogenic context, in central Europe, the narrow Rhenohercynian Basin was closed and inverted (Franke *et al.* 2017), producing thin-skinned nappes containing Devono-Carboniferous strata underlying the Weald and Wessex basins in southern England (Butler 2018). Orthogonal closure and crustal shortening of the Rhenohercynian Basin brought the North Armorican promontory of the Variscan internide zone and intervening accreted crust of the Saxothuringian Zone beneath the English Channel into closer juxtaposition with the ABM.

The crust underlying the Permo-Mesozoic Worcester Graben (representing the inverted stump of the Worcester Proto-graben) resembles a wedge driven into the Variscan foreland, separating the Welsh Massif in the west from the ABM (Fig. 11). The schematic cross-section in Figure 12 shows strong uplift between the Malvern Line in the west ('Malvern Axis thrusts') and the Alcester Thrust in the east (Chadwick and Smith 1988; Barclay *et al.* 1997). There are close analogues to these uplifted wedges in 'mountain front uplift' structures such as the Wind River Uplift east of the Rocky Mountains, as recognised by Smith (1987) and by Peace and Besly (1997). Evidence for this 'Malvernian' phase of uplift was, however, identified much earlier from studies of outcrop in the Malvern and Abberley Hills (e.g. Groom 1902) and



in the clast content of Late Carboniferous and Early Permian formations in the Midlands coalfields (Trueman 1946, 1947; Wills 1948). To better reflect its mountain-front origin, the term 'River Severn Uplift' (e.g. *see* Fig. 10) was introduced by Pharaoh (2018) for this structure, previously referred to as the Worcester High by Smith (1987). In Figure 13 *(overleaf)*, the River Severn Uplift is located opposite a 'pinch-point' in the Variscides, adjacent to the Archaean crust of the North Armorican promontory. It appears that the strong crust of this Archaean nucleus was perfectly positioned as an indenter to focus orogenic stress and exploit the mechanical weakness of the Malvern Line.

Strong inversion occurred on both flanks of the structure, apparently directed westward on the Malvern Line (Chadwick 1985), and eastward in a fold-thrust belt on the edge of the concealed Oxfordshire-Berkshire Coalfield (Chadwick and Smith 1988; Peace and Besly 1997; Barclay *et al.* 1997). The 'apparent' translations identified on E–W oriented 2D seismic sections cannot of course constrain the magnitude of any component of strike-slip on the same structures, which, given the N–S Variscan compression, could have been significant. Reverse movement also occurred on other reactivated structures farther north in the foreland (e.g. see Corfield *et al.* 1996). Close to the Malvern region, these included the Warton Fault bounding the Nuneaton early Palaeozoic inlier, and the Thringstone Fault bounding the south-west edge of the Charnwood Forest block.

Uplift along the N–S trending axis of the proto-graben resulted in removal of perhaps 3km of early Palaeozoic strata, together with any Devonian and Mississippian strata, and erosion down to the Precambrian level, as proved in the Kempsey Borehole. The effect of the uplift is reflected clearly in the subcrop patterns of the Somerset and Bristol Coalfield to the west of the Malvern Line, and of the concealed Oxfordshire-Berkshire Coalfield, east of the Inkberrow-Haselor Hill-Lickey End fault system (*see* Fig. 11).

A further complication is the possible reorientation of the orogenic stress field to E–W compression, in Stephanian to Early Permian time, reflecting collision in the Uralide Orogen (Ziegler 1990; Pharaoh *et al.* 2018). Late Variscan reorientation of the stress field was invoked by French geologists (Gélard *et al.* 1986; Blès *et al.* 1989), and subsequently supported by Ziegler (1990), to explain the apparent structural complexity of internal Variscide massifs. Although the hypothesis has fallen out of favour in France (e.g. Faure 1995), it was adopted by Pharaoh *et al.* (2018) to explain the geometry of N–S trending fold structures of latest Pennsylvanian–Early Permian age in the East Irish Sea, Midland Valley and Forth Approaches of Scotland, and elsewhere. Any E–W compressive intraplate stress superimposed on the River Severn Uplift would have further facilitated its uplift and erosion, as described in the next paragraph.

The Clent Breccia of earliest Permian age (*c.* 298Ma) has a highly variable clast composition, and records the rapid erosion of the River Severn Uplift down to its Precambrian core within perhaps 10Ma. The possibility of previous uplift and erosion during Penobscotian (Early Ordovician) and Acadian (Early Devonian) orogenic phases cannot be entirely excluded. A major stratigraphic hiatus of *c.* 20Ma is associated with the Saalian and Altmark unconformities recognised in central Europe (Ziegler 1990; Gast *et al.* 2010). In Late Permian time (*c.* 260Ma), the Worcester Graben began to subside between the ABM and the Welsh Massif, preserving up to 1.5km of the Late Permian aeolian Bridgnorth Sandstone.

Figure 12 (previous page) Restored schematic cross-section (cf. Fig. 4), to illustrate the structural evolution of the region (reproduced from Barclay et al. *1997): a = Late Carboniferous times, before Variscan movements; b = Variscan compression leads to crustal shortening and apparent reverse faulting ('positive inversion') along the Malvern Axis and thrust, and development of a mountain-front uplift; c = end-Carboniferous to Early Permian times-regional uplift and erosion enhanced by Uralian intra-plate stress; d = Permo-Triassic tension leads to extensional reactivation of Variscan fractures, with subsidence ('negative inversion') controlled by major basin-margin normal faults. Note that this simplified model does not incorporate the evidence for late Cambrian-Tremadocian subsidence (the Worcester Proto-graben or 'aulacogen') or possible earlier phases of inversion, during the Penobscotian (Early Ordovician) and Acadian (Early Devonian) orogenic phases.*

Mesozoic–Cenozoic evolution

In Early Triassic time (Scythian, *c.* 246Ma), Britain was almost completely occupied by the deserts in which the 'New Red Sandstones' were deposited (Warrington and Ivimey-Cook 1992). Dominantly fluviatile sandstones of the Sherwood Sandstone Group were deposited in a vast braided river system extending from Northern Armorica via a fairway through south and central England to marine basins in the southern North Sea and Irish Sea (Whittaker 1985; Smith 1985; Newall 2017). This fairway was tectonically controlled by, and entrained within, the rapidly subsiding Worcester Graben. The main syndepositional graben-bounding faults — the East Malvern Fault in the west (Chadwick 1985) and the Inkberrow-Haselor Hill-Lickey End Fault System in the east (Chadwick and Evans 2005) (Fig. 12) — developed as extensional shortcuts in the hangingwall of the Variscan compressional faults at the margins of the River Severn Uplift, described above. Up to 2.5km of Sherwood Sandstone Group strata, and the overlying Mercia Mudstone Group, accumulated in the Worcester Graben, which, along with deep graben in the southern North Sea, Cheshire Basin, Eastern Irish Sea and North Channel, formed part of the Permo-Triassic Central European Basin System (Scheck-Wenderoth *et al.* 2008). The latter is a N–S trending rift system reflecting E–W extension, which initiated the break-up of the Pangaea Supercontinent. Latest Triassic strata (Rhaetian, *c.* 207Ma) represent a marine incursion penetrating into the graben.

In Jurassic time, extension reoriented to a N–S direction, associated with the rotation of Iberia and the opening of the Bay of Biscay (Chadwick *et al.* 1989), so that the favourably orientated, E–W striking Variscan compressional structures south of the Variscan Front in southern Britain were reactivated in extension. Despite this, subsidence in the Worcester Graben continued, Jurassic strata thinning eastwards onto the London-Brabant Platform (Whittaker 1985). Cretaceous and Cenozoic strata are absent from the Worcester Graben, so the contemporary history can only be surmised indirectly from surrounding regions. It is likely that rising sea level in Middle to Late Cretaceous time coupled with regional thermal subsidence enabled the Upper Greensand and Chalk groups to blanket the ABM, including the Worcester Graben, leaving the Welsh Massif as the nearest landmass (Hancock and Rawson 1992); however, these strata were entirely removed following Alpine uplift in Cenozoic time. The Welsh Massif, decoupled from the ABM by the Malvern Line-Worcester

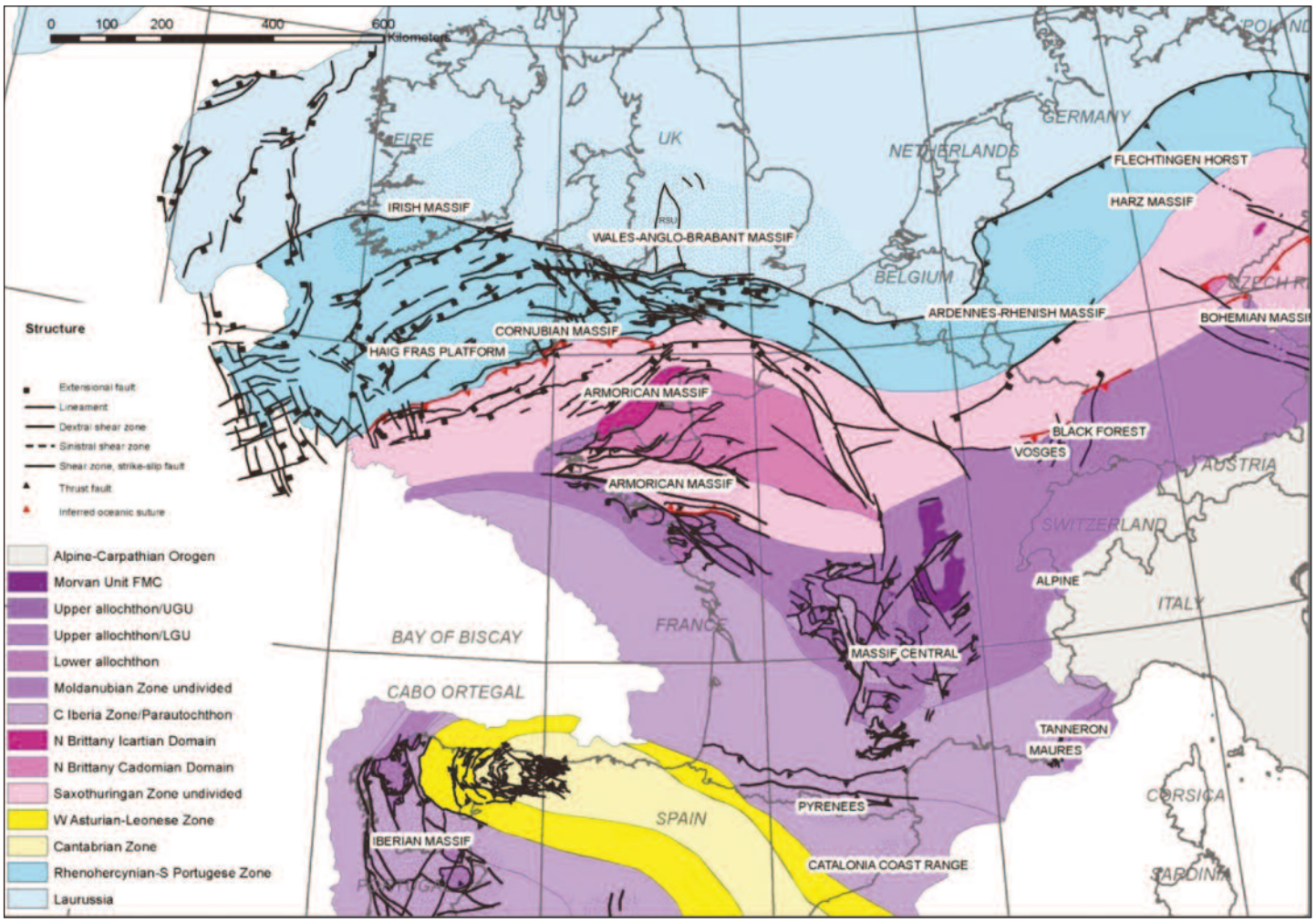


Figure 13 Variscan orogenic terranes of western Europe. Note the juxtaposition of the River Seven Uplift (RSU) to a pinch-point in the Rhenohercynian Terrane resulting from indentation by the Archaean Icartian Domain embedded within the Cadomian North Brittany Terrane (after Pharaoh et al. *2017).*

Graben, suffered intermittent uplift and erosion of its Mesozoic and Cenozoic cover, probably as a result of thermally induced uplift associated with plume magmatism (Brodie and White 1994) and opening of the North Atlantic during early Cenozoic time.

Conclusions

The long and complex tectonic history of accretion and reactivation of the crust in the Malvern-Worcester Graben region can be summarised as follows:

- early calc-alkaline arc magmatism (680–660Ma) at the Amazonian margin of Rodinia
- almandine-amphibolite and greenschist metamorphism/ductile deformation (650–610Ma)
- uplift of the meta-igneous Malverns Complex *(c.* 600 Ma)
- arc-marginal basin formation (566–560Ma)
- 'Avalon Orogeny', terrane amalgamation and suturing (*c.* 545Ma)
- development of Worcester 'Proto-graben' near the Gondwana margin (Cambrian-early Tremadoc)
- Penobscotian Phase (Early Ordovician) — ?inversion of proto-graben
- Avalonia's drift from Gondwana (post-Arenig)/subduction of Iapetus-Tornquist ocean (Ordovician)/subduction shutdown (Ashgill)
- gently subsiding shale-carbonate platform with local small extensional basins (Silurian)
- tholeiitic and calc-alkaline volcanism (Early to Middle-Silurian) — ?subduction and closure of the Rheic Ocean
- Acadian Phase (Early Devonian) — ?further inversion of proto-graben
- extensional reactivation of basement structures in surrounding regions (Carboniferous) — Malverns and Worcester Basin part of the Wales-Anglo-Brabant Massif
- Variscan Orogeny (late Westphalian-Stephanian) — positive inversion and creation of the 'River Severn Uplift' as a 'mountain front uplift
- Uralian Orogeny (Stephanian–Early Permian) — intra-plate stress from Uralian Orogen enhances uplift
- extensional reactivation and formation of Worcester Graben (Permo-Triassic, Jurassic and ?Cretaceous)
- ?Alpine inversion, uplift and erosion (Cenozoic)

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Figure 5 is based on maps of the Acadian Unconformity developed by Nigel Smith throughout his career at the British Geological Survey. A review by Bill Barclay is gratefully acknowledged. This paper is published with the approval of the Executive Director, British Geological Survey.

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From holy well to expensive bottle — the history and hydrogeology of the Malvern waters

John D. Mather

Emeritus Professor of Geology, University of London

[Editor's note: Unfortunately, Prof. Mather was unable to attend the Symposium to deliver his lecture, so he has provided us with an extended abstract of his topic — the Malvern Waters. Prof. Mather has kindly agreed to give the Keynote Lecture in 2019 at our OUGS AGM. Prof. Ian Fairchild, who delivered the Symposium Keynote Lecture (see page 7), kindly stepped in to provide a talk on Malvern springs and their history. Together with Dr John Payne, he has given us an article on his 'springs' talk and on the geology of the Malverns springs. This material was published earlier as two short articles in Earth Matters: The Newsletter of the Geology Section of the Woolthorpe Naturalists' Field Club. *The OUGS is grateful for permission to use this material.]*

The Malvern Hills have long been celebrated for the properties of their waters, with the earliest documented evidence of their use dating to the middle of the 16th century. 18th century analyses by Dr John Wall, a Worcester physician, were to show that the waters were characterised not by any unique mineral content, but by their relative purity, leading to the famous rhyme:

The Malvern water,
says Dr John Wall,
Is famed for containing
just nothing at all!

For more than 400 years Malvern spring waters have variously provided the source for medieval holy wells, 18th century spas, 19th century hydropathics and 20th century bottled waters. The quality requirements for these various uses vary and the Holy Well at Malvern and St Anne's Well at Buxton are probably the only water sources in the UK that have made this transition.

The central axis of the Malvern Hills is formed of Precambrian schists and gneisses. To the east, these are faulted against Triassic rocks and to the west against Palaeozoic strata. The spring discharges are located along the boundary faults and within the Precambrian outcrop itself. Water from springs within the schists and gneisses is weakly mineralised and shows marked fluctuations with rainfall, suggesting derivation from shallow flow systems. The fault springs are more strongly mineralised and show the effects of longer residence times and increased water/rock interaction.

The waters of medieval holy wells were usually of good quality and were prized for their purity and sweetness. They had no intrinsic healing properties and waters were believed to heal because of their association with a saint or local holy man, or with a building, landmark or gathering place associated with them. Some carried saints' names, but many were just called 'holy well'. The Holy Well at Malvern lies on the western side of the old coach road heading north towards Great Malvern, and may have been given the name as it was the only identifiable place in a lonely and wild part of the countryside, a traditional resting place on the journey north. The other source with a sacred name is St Ann's Well above Great Malvern, but this name first appears in the 18th century, and may have been bestowed on the spring to give it extra prestige by an enterprising owner or tenant. Both the Holy Well and St Ann's Well were fed by water derived from the Precambrian rocks and are weakly mineralised.

In the mid-18th century John Wall began to advertise the Holy Well and St Ann's Well as spas at which patrons could both drink and bathe in the waters. Spa waters were generally distinguished by their distinctive, usually unpleasant, taste derived from high concentrations of dissolved minerals, whereas Malvern water was marketed on the basis of its exceptional purity. Initially facilities were primitive and in 1757 there was only one lodging house with furnished accommodation for about 15 people. Over the years, visitor numbers increased, with new hotels built in Great Malvern and hot and cold baths added. However, it still remained as an insignificant rural spa until 1842 with the arrival of Dr James Wilson, who had spent the previous year at Graefenburg, in Austria, the birthplace of hydropathy. Wilson and his partner, James Manby Gully, were looking for a site for an English Graefenburg, which required a plentiful supply of water, clean air and easily climbed hills close by. Malvern was ideal and was soon invaded by other aspiring water cure doctors. By mid-century the village spa had become a prosperous town. Gully was to become the most famous of the practitioners and his patients included Charles Darwin, Florence Nightingale and Lord Tennyson. The establishments exploited both the hillside springs and the fault springs with their greater mineral content. So many of the water sources were developed for hydropathy that the town's water supply was put under severe pressure, a situation that was not resolved until 1894 with the completion of the British Camp Reservoir.

Water from the Holy Well was bottled on a limited basis from the middle of the 18th century. In the 19th century it became a more formal business, and Schweppes exhibited bottled water from the Holy Well at the Great Exhibition in 1851. Schweppes later switched production to a fault spring on the western side of the hills, where Malvernian rocks were faulted against Silurian Wenlock Shales. Schweppes withdrew from the Malverns in 2010, as they were unable to extract the volume required to compete on price in the very competitive bottled water sector. After a period of inactivity, during which the buildings became dilapidated, bottling at the Holy Well restarted in 2009 and continues today.

Much of the publicity associated with the springs suggests that the water of the Holy Well, St Ann's Well and other hillside springs has been stripped of its dissolved minerals during deep circulation through the dense Precambrian bedrock. In fact, the lack of mineralisation results from short flow paths, which provide little opportunity for the dissolution of the rock forming minerals. These short flow paths mean that yields are closely related to rainfall, which restricts development of the springs, as less water is available during hot dry periods when demand is at its highest. The hillside spring sources are also more susceptible to bacteriological contamination and the water currently bottled from the Holy Well requires treatment and has to be marketed as 'spring water' rather than as 'natural mineral water'.

The Holy Well, St Ann's Spring and other wells and springs can still be visited, but the water doctors are long gone, and their premises converted into apartment blocks and offices. Today the Malverns are a resort for walkers and tourists rather than for water drinkers!

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Malvern's springs — a geological perspective

John Payne

Herefordshire and Worcestershire Earth Heritage Trust

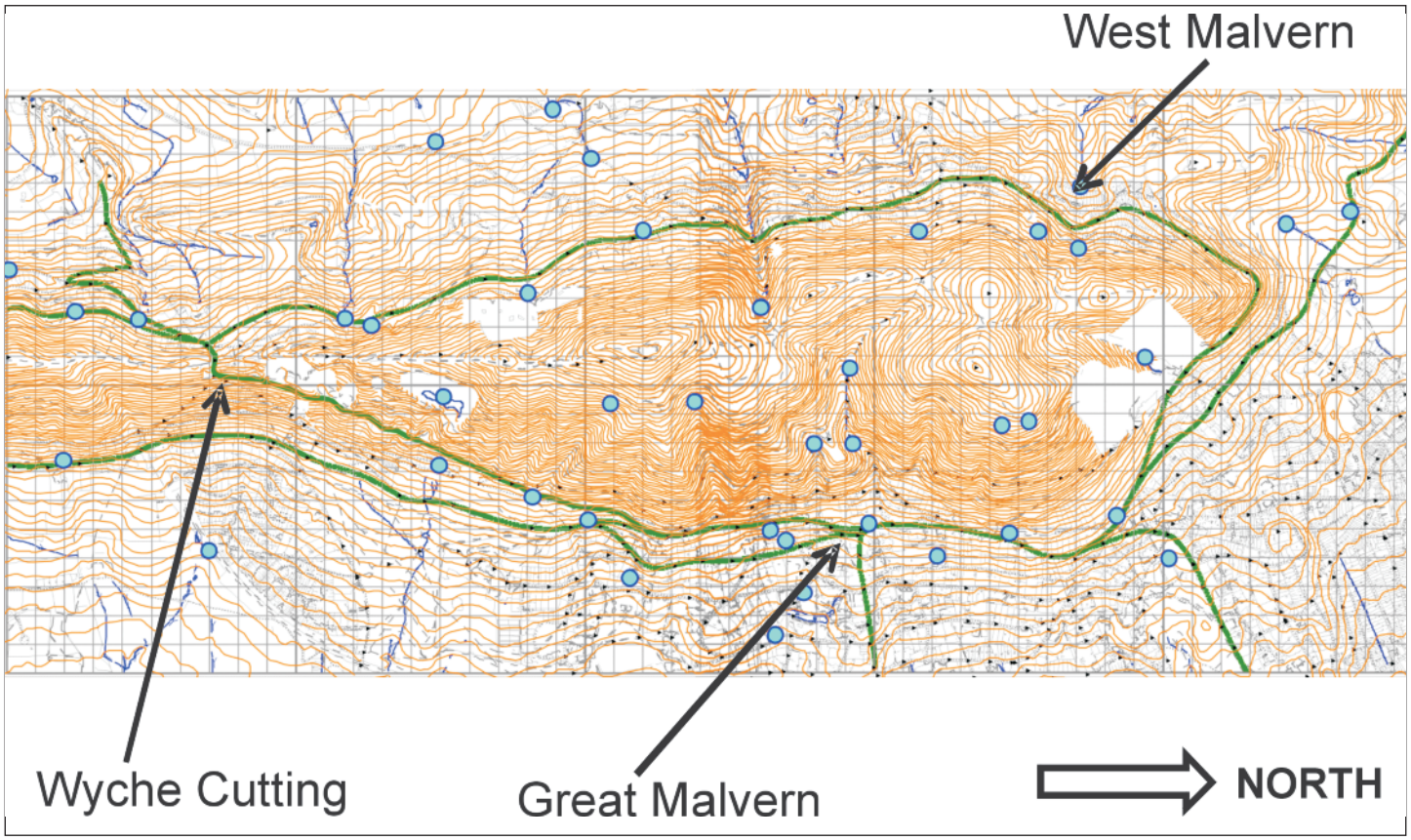
The springs of the Malverns Hills were first discussed scientifically in the 17th century, the interest lying in the curative properties of the waters (Bannister 1622; Beale 1666). Publications in the 18th and 19th centuries showed chemical analyses of the spring waters. Only in the early 20th century was any attention paid to the geological conditions that give rise to the springs (e.g. Thorpe 1907; Wickham 1911) but, after Richardson's 1930s 'Wells and Springs' series for the Geological Survey, very little was forthcoming except for the writings of the Malvern Spa Association (MSA) and descriptions of the springs in books by Weaver and Osborne (1992) and Osbourne and Weaver (1997). An MSc project report (Sawyer 2002) is the most comprehensive account of the hydrogeology of the Malvern Hills.

An account of the geology and basic hydrogeology of the Malvern Hills and their immediate surroundings appears on the MSA website. A wide variety of rock types is present locally, with ages ranging from 700 to 220 million years, and with much more recent erosion products as a thin layer on the surface.

Igneous and metamorphic rocks consisting of interlocking crystals of various silicate minerals form the body of the Hills. These very hard rocks are quite impervious and almost insoluble in water. The Malvern rocks (the Malverns Complex) lie essentially as a slab of rock several hundred metres thick sloping downwards to the east at about 30° to a depth of at least several kilometres. The top edge of the slab forms the ridge of the Hills. Since their solidification from molten rock nearly 700 million years ago the rocks have been subjected several times to major tectonic events. In these very slow but violent events the rocks were broken and the resulting network of fractures enables the storage and transmission of water within the Hills. The earliest and often large fractures have since been filled with rock fragments, which have been cemented into an impervious mass. The most recent faults and joints, about 300 million years old, have generally remained open and connected, and form the Malvern Hills aquifer of today. This crack network extends probably throughout the whole of the rock body, so that rainwater will have penetrated to large depths and now fills the aquifer to somewhat above the level of the surrounding terrain. This situation gives rise to the many springs that lie around the Hills at the surface junction of the Malvern rocks, with the generally impervious clays and sandstones that border them. This junction is known as the 'spring line'.

Figure 1 shows a map of the Hills north of the Wyche. Marked are all the recorded water sources that can reasonably be identified as springs and not spouts deriving their water from distant springs. Some of these springs are now permanently dry.

Figure 1 The northern Malvern Hills showing positions of the known springs, i.e. not significantly engineered (north is to the right. The main roads are shown. Great Malvern is at the bottom-centre of the map. The Wyche Cutting is toward the left side. The many brown lines are contours at 5m intervals. The grid is at 100m spacings) (© Crown copyright and database rights 2019 Ordnance Survey (100025252).



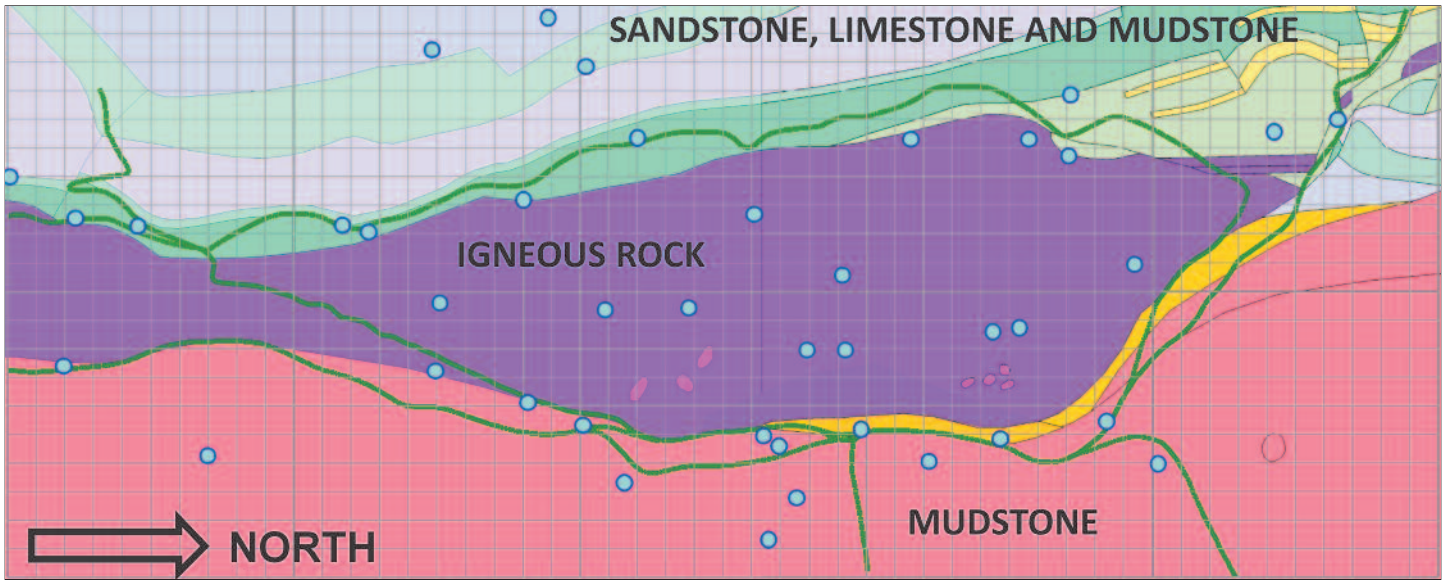


Figure 2 The north Malvern springs in their geological settings (Geological Map Data BGS © UKRI 2019) (© Crown copyright and database rights 2019 Ordnance Survey (100025252).

Figure 2 shows the general geology of the area. The spring line is the boundary of the mauve area, which indicates the Malvern rocks. The main road around the northern hills generally is close to the spring line and many springs are found near it. However, it is clear from the map that a number of springs lie higher and lower on the hill.

The sources, which lie high on the hill, are of two types. The first type issues on the open hillside; the second on valley floors. Examples of the first type are the Dripping Well, not far below the Worcestershire Beacon, and the spring in the Dingle. Another, on North Hill, is shown in Figure 3. These springs are sourced from aquifers of fractured Malvern rocks where the system of fractures is not connected to that in the main rock body, thus forming a separate isolated aquifer. Probably any connecting cracks have been filled and blocked by eroded material over long time periods.

The valley-floor type of spring is depicted in Figure 4 *(overleaf)* and is exemplified by the source of the stream in Green Valley, above Great Malvern, and the now-enclosed spring in Rocky Valley, which fed the North Malvern tank at the clock tower. Here, rubble eroded from the hillside above has collected on the valley floor. Rain falling in the valley or issuing from the adjacent fractured rock runs in a channel at the base of the rubble to emerge where the valley floor becomes steeper, so that the thick rubble layer cannot be maintained. The visible valley floor is of rock and soil; the open channel below is kept open by the

Figure 3 The highest spring on the Malvern Hills after a rainy period. It is located at SO 7712 4652, only 42m lower than the summit of North Hill. The water runs downhill for a few metres before disappearing underground.

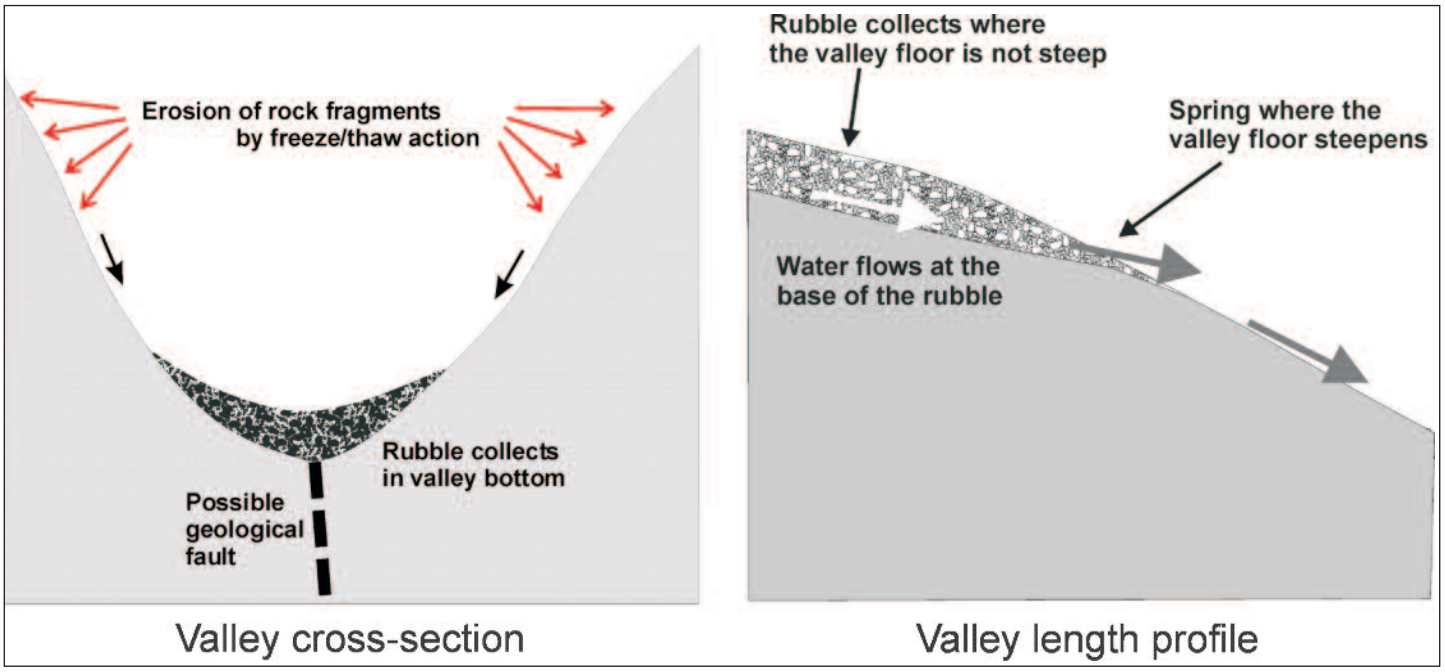


Figure. 4 Diagram of the valley floor springs.

flow of water. In some places, such as in Rocky Valley, the underground flow can be heard after periods of wet weather. The large valleys on the Hills, such as Green and Rocky Valleys, are believed to have formed on the lines of major geological faults. These faults are very ancient and are assumed to be now blocked to water flow by consolidated debris. Early faults full of impermeable fault breccia are common on the Malvern Hills.

Figure 2 shows several springs on the impervious mudstone rock below the spring line. These have sometimes been attributed to issue from below via faults in the mudstone. It seems to this author to be more likely that these springs are similar in nature to the valley-floor springs described above. Much of the land adjacent to the Hills is covered in eroded material and, probably just after the Ice Age, flow channels were established, which have been maintained during the subsequent accumulation of soil and vegetation.

Little is known of the details of water flow within the Hills. It is a topic difficult to investigate. Even the length of time that water spends in the aquifer between rainfall and emission at springs is not well known, and of course varies with location and recent rainfall history. A typical value is about 30 days. A second important parameter of the hydrogeology is the fraction of the rainfall that emerges from the springs. A few estimates by various authors lie between 20% and 25%. The remaining large fraction is lost by evaporation, transpiration and small-scale seepages from the aquifer in amounts not large enough to generate springs.

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Malvern's springs — what's in the water?

Ian Fairchild

Herefordshire & Worcestershire Earth Heritage Trust, Geological Records Centre, University of Worcester, Henwick Grove, Worcester WR2 6AJ

Figure 1 Dr John Payne next to Hayslad Well on the western flank of the Malverns Complex. This site is extensively used as a source of water by local people (photo: John Gunn).

Many people in the Malvern area go to some trouble to collect spring water for using at home (Fig. 1), but what is special about the water? It is not a secret that the local springs actually show quite a variation in composition, maybe enough to taste the difference. The best-known water nationally came from Primeswell Spring on the western flank of the hills near British Camp. This was the source of the water formerly bottled by Cadbury-Schweppes as Malvern spring water at the village of Colwall west of the Malverns until 2010 (the spring site is inaccessible today). Small-scale bottling is currently undertaken at Holy Well (Fig. 2) following a long tradition dating back to the 1620s. It was the subject of the famous claim by local physician John Wall in 1757 that the water contained "nothing at all"!

The article by John Payne *(this volume p52)* explains the geological framework: the substrate through which the water has flowed underground. Here I have gathered together various water analyses from the sources listed in his article, together with an unpublished set from 1996 kindly supplied by Professor Jon Blundy. They demonstrate some coherent patterns of variation.

To demonstrate this, I have used a series of cross-plot graphs. These show interesting differences between typical streams emerging from the crystalline Malverns Complex rocks in the core of the hills versus those that have flowed through the sedimentary rocks on the west and the east of the hills. I have also differentiated analyses of the Primeswell and the Holy Well water.

Each of the plots is against pH on the horizontal axis. Waters lying to the left are acid and those further to the right are alkaline. The weak acidity of rainwater is neutralised by dissolving minerals. Acidity is also generated in soils leading to more dissolution of minerals, but this is typically neutralised by expelling carbon dioxide at springs.

Figure 2 (a) (above) The building housing the Holy Well. This site is based on the Malverns Complex and lies to the south of Great Malvern; (b) (below) the Holy Well during the annual Well-Dressing Festival. (photos: Ian Fairchild).

Figure 3 shows the total amount of 'dissolved solids' on the vertical axis. The springs based on the Malverns Complex rocks stand out as containing little dissolved matter, and for some folk historically this purity is a much sought-after feature. As noted above, the Holy Well water belongs to this group, but the water at St. Ann's Well is even lower in dissolved solids. In contrast, the late-lamented Malvern Water at Primeswell does not have a distinctive composition, being more typical of tap-waters generally.

Figure 4 illustrates the variation in hardness of the water expressed as the equivalent amount of calcium carbonate dissolved in the water (although some hardness also comes from magnesium). Calcium carbonate dissolves more readily than other common minerals, apart from certain salts, and its concentration tends to increase as pH rises. There are some exceptions where pH is lower than expected and these correspond to springs that have not yet degassed excess carbon dioxide. Traces of calcite are found in most rocks, including granites. Nevertheless, dissolved calcium carbonate tends to be higher in the western spring waters as expected because of the presence of limestone in this area.

Figure 5 examines sulphate variation with pH. Again the purity of the Malverns Complex springs stands out. High sulphate occurs more often in the eastern springs than the western ones. This could be because of traces of calcium sulphate (gypsum) in the Mercia Mudstones to the east, but sulphate also forms by oxidation of iron sulphides (pyrite, or fool's gold), which is widespread as a trace mineral.

Figure 6 *(opposite)* shows nitrate on the vertical axis. It is good to report that hardly any waters are above the EU suggested limit of 50mg/litre and most are below 10mg/litre, particularly on the Malvernian rocks. Nitrate in lowland areas in general tends to be high because of fertiliser application, whereas livestock are the main source on the hills.

Finally, Figure 7 *(opposite)* shows chloride on the vertical axis. Most of the Malvernian Complex springs have very low chloride and these values are probably close to the small amount of sea salt found in the rain in our area. What is interesting is how large the chloride values are in many other springs, being many times higher. Although an origin by concentration of salt by evaporation in soils and unconsolidated sediments near the ground surface is conceivable, another explanation appears more likely. Road salt application is a major source of sodium chloride to catchments and all of the sites with high chloride are in a position to be contaminated in this way. It is salutary that the samples were all collected in the summer, some months after salt application.

I haven't touched on another aspect of water quality — the presence or absence of harmful bacteria. Monitoring by the Environment Agency shows that this is not normally a matter of concern except at one or two vulnerable sites, which are not used as water sources. Nevertheless, at times of exceptionally high or low flow the risk is heightened and, unlike tap water, the water is not continuously monitored for drinking purposes.

Key to the groups of springs shown in Figures 3 –7.

- Central springs (Malvern complex)
- Western springs
- Eastern springs
- Primeswell (source for the former Malvern bottled water)
- Holy Well

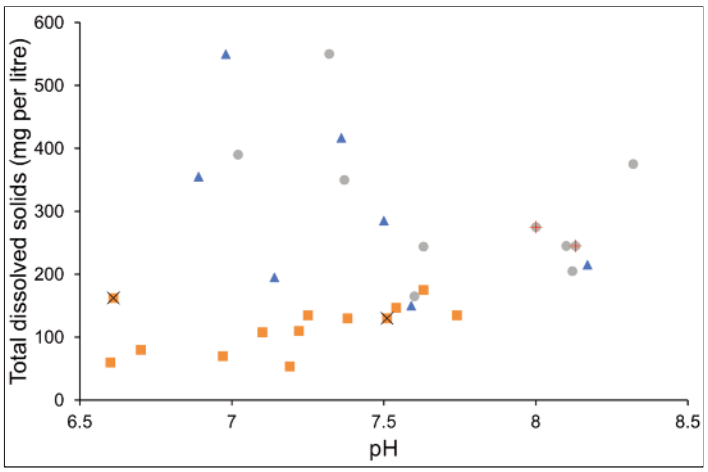


Figure 3 (above) Cross-plot of total dissolved solids versus pH.

Figure 4 (below) Cross-plot of water hardness (expressed as equivalent dissolved calcium carbonate) versus pH.

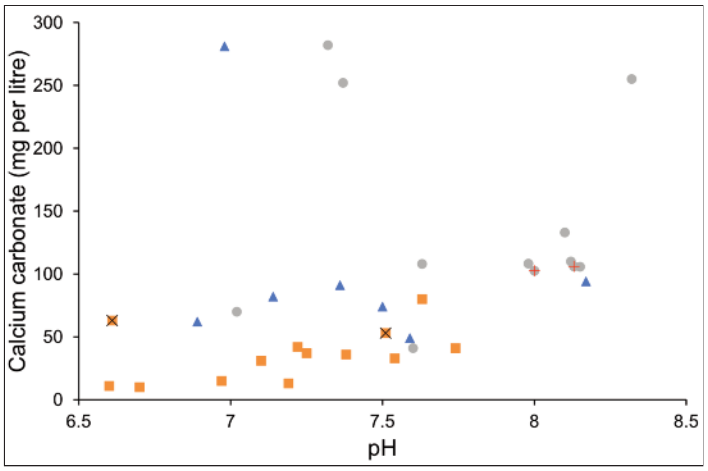
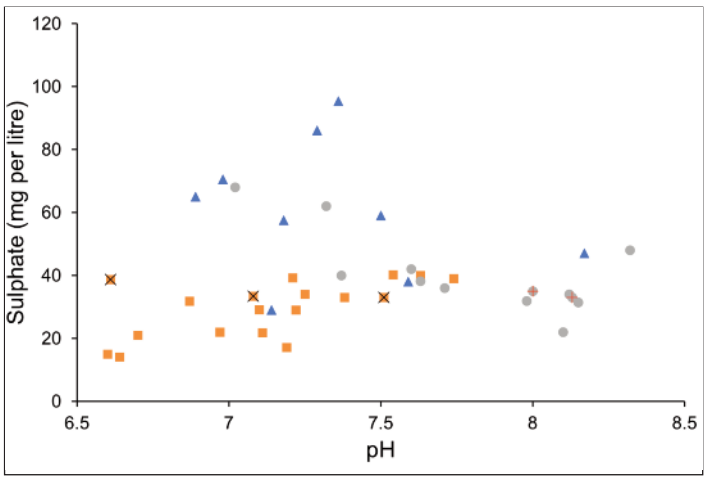


Figure 5 Cross-plot of dissolved sulphate versus pH.



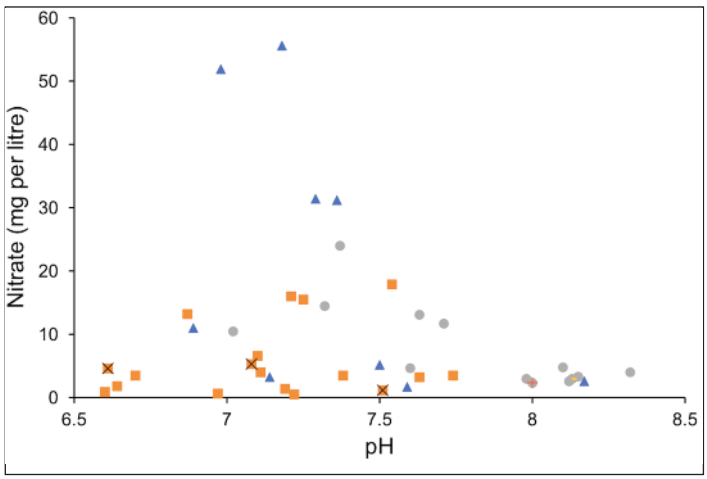


Figure 6 Cross-plot of dissolved nitrate versus pH.

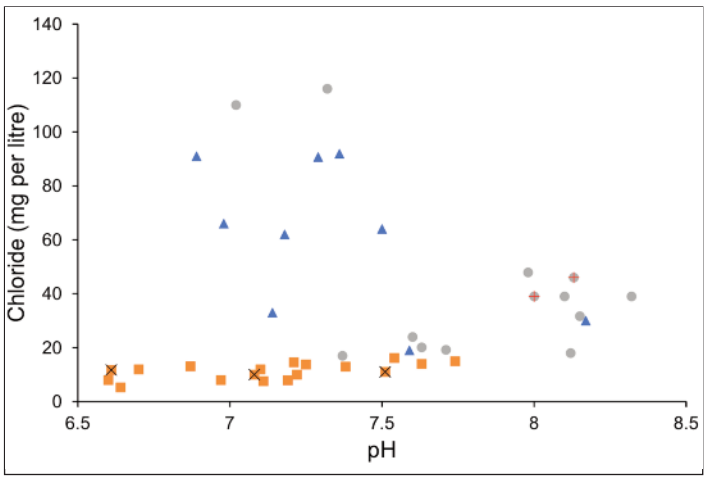
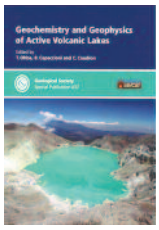


Figure 7 Cross-plot of dissolved chloride versus pH.

Book review



Obha, T., Capaccioni, B., and Caudron, C. (eds) 2017 *Geochemistry and Geophysics of Active Volcanic Lakes*. London: Geological Society Special Publication 437 (ISBN 978-1-78620-244-4; 295pp; hardback £100, £50 to GS Fellows)

During the 20th century, subaqueous eruptions accounted for just 8% of volcanic events, but led to 20% of the total fatalities resulting from them. This Geological Society of London Special Publication is therefore welcome in highlighting a geohazard about which few geologists may be familiar.

The book is dedicated to one of the co-editors, Professor Bruno Capaccioni, who was killed in a car accident before publication.

As with most GSL Special Publications, this volume is a collection of research papers. It is divided into two main sections, acidic lakes and neutral lakes, and is slightly unusual in that many of the papers relate to just two volcanic events: the eruptions at Lake Nyos and Lake Monoun in Cameroon.

In 1986, more than 1,800 people were killed in a single event at Nyos, owing to carbon monoxide poisoning. This hitherto relatively little-known volcanic lake became the focus of much attention regarding the cause of the CO^2 eruption. The papers discuss the debate regarding the origin of the CO^2 and the research undertaken into the geochemistry and hydrothermal system feeding the lake. Other papers outline the various steps that had to be taken to 'degas' the lake to safe levels to avoid further eruptions. These have been successful and monitoring on a regular basis takes place to warn of future, potentially dangerous, new gas build up.

A similar event had taken place at Lake Monoun two years earlier, but the death toll was lower (37) and did not attract the same attention as Nyos.

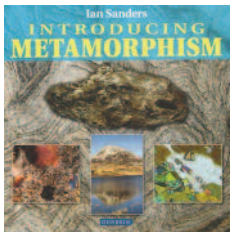
Read together, the research papers form an excellent account of the geological detective work at Nyos, how limnic eruptions occur, mitigation and identification of possible further sites where they may occur.

Other active lakes are also covered, such as the passively degassing Kawah Ijen in Indonesia, the acid crater lake at Taal Volcano in the Philippines and a particularly interesting paper about the Newberry Volcano twin crater lakes in Oregon, USA, which, despite their being within a single caldera and having divided 7ka ago, have different geochemical characteristics.

Overall, this book represents the latest in research into an overlooked topic. It offers an introduction to crater lake basics and more but, by telling the Nyos story, it provides a framework resulting in an extremely interesting and informative book. The reviewer feels that this would be an excellent starting point for students looking for a topic for their SXG paper.

— Nigel Combley, BSc Hons Geosciences (Open), FGS

Book review



Sanders, Ian 2018 *Introducing Metamorphism*. Edinburgh: Dunedin (ISBN 978-1-780460-64-2; 148pp; paperback £14.99)

Sometimes, just when you need something, it actually turns up. This was the case with this lovely little book. I wanted to undertake more study of structural geology and revision of metamorphism seemed like a good idea. But where to start! Well, this book by Ian Sanders of Trinity College Dublin has met my need.

The book is quite small (22cm x 22cm and 1cm thick). It only has 148 pages, but the level of information contained within those pages is immense. It is called 'Introducing Metamorphism' and that might give the impression of being rather simplistic. Far from it. The level of information given ranges from simple to (in my case) really complicated — it has certainly made me think and I have learned new information (I finished my OU degree nearly 20 years ago and some data in this book are only a few years old) in addition to revising what I (thought) I already knew.

The book has five main chapters: 'Introduction', 'The Petrography of Metamorphic Rocks', 'Interpreting Mineral Changes and Textures', 'Aureoles, Orogenies and Impacts', and 'Case Studies in Geothermobarometry'. It also has five appendices: 'The Earth's Interior', 'The Chemical Formulae of Minerals', 'Minerals under the Microscope', 'Microbeam and X-ray Methods', and 'The Principles of Isotopic Dating (Geochronology)'. Finally, there is a fairly comprehensive Glossary and some suggestions for Further Reading. The book is well illustrated and refers the reader to the OU's Virtual Microscope (VM) (www.virtualmicroscope.org) and the VM GeoLab. *[Editor's note: VM is no longer exclusively the OU's, but is now university-wide in the UK and Ireland.]*

The book reads fairly easily, although it makes you think. The author suggests when to read the appendices (each one is generally applicable to a particular chapter), which I found very helpful. The images in the book are good quality, although in electric light some of the colours in cross-polar light (XPL) images (taken from the VM) are difficult to make out (my eyes, plus shiny paper). There are a few typos and I thought I found one instance of a figure being referred to where the figure number seemed to be incorrect; hardly a problem in the great scheme of the book.

I found this book a fascinating read and having done so from cover to cover, I am now about to start again. This time I will be using the Virtual Microscope where, apparently, I will be able to move the turntable and see more. I have not used the VM before — it did not exist when I did my degree. We had to use an actual scope with thin sections!

Would I recommend this book? Yes, but absolute beginners may want to take it slowly and not worry too much if there are bits they do not fully understand. There is such a lot of information and some parts need reading several times. Another success from Dunedin's 'Introducing' series.

— Jane A. Michael, BSc (Hons) (Open)

Non-biostratigraphic correlation techniques and their role in stratigraphy: examples from the Wenlock Series (Silurian) of the Midland Platform, England

David C. Ray*, Emilia Jarochowska, Helen E. Hughes and James R. Wheeley

* Corresponding author: daveray01@yahoo.com

DCR and JRW — School of Geography, Earth and Environmental Sciences (GEES), University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

EJ — GeoZentrum Nordbayern, University of Erlangen-Nuremberg, Loewenichstr. 28, 91054 Erlangen, Germany

HEH — School of Geography, Earth and Environmental Sciences, Fitzroy Building, Plymouth University, Drakes Circus, Plymouth PL4 8AA, United Kingdom

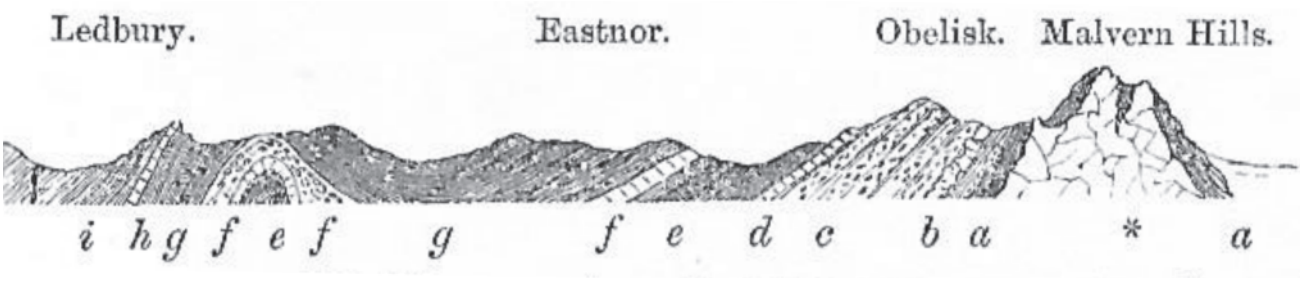


Figure 1 Section from the Malvern Hills to Ledbury: the Wenlock Succession consists of the Woolhope Limestone Formation (d), Coalbrookdale Formation (e) and Much Wenlock Limestone Formation (f) (from Murchison 1872, 95).

Introduction

Biostratigraphy is the principal means by which correlations can be made between sedimentary successions, and the compilation of the relative distribution of fossils forms a mainstay in the development of the geologic timescale. However, the incomplete nature of the stratigraphic record places limits on the application of biostratigraphy within many successions. In particular, age-diagnostic fossils can be absent or rare, and their consequent stratigraphic distribution unreflective of their total stratigraphic range.

The Wenlock Series of the Midland Platform has been studied in detail since the foundation of the Silurian System (Murchison 1839) (Fig. 1), and the importance of this area was formally recognised in the 1980s with the establishment of the Global Boundary Stratotype Section and Points (GSSP) that define the Wenlock and its constituent stages (Sheinwoodian and Homerian) (Melchin *et al.* 2012). Thus, the successions that crop out within Herefordshire, Shropshire, Worcestershire and the West Midlands are among the most intensively studied of Wenlock rocks (Fig. 2). Nonetheless, age-diagnostic fossils, such as chitinozoans, conodonts and graptolites, are far from common resulting in age and correlation uncertainties (Cocks *et al.* 1992).

The gaps in the biostratigraphic record can be filled by alternative correlation techniques, and within the Wenlock of the Midland Platform volcanic ash horizons (bentonites), sedimentary facies changes resulting from sea level changes (sequence stratigraphy) and variations in the carbon isotopic record (carbon isotopic stratigraphy) have all been used. These correlation techniques, applied alongside the available biostratigraphy, have resulted in significant improvements in our ability to correlate across the Midland Platform and beyond. What follows is a summary of the application of these alternative correlation techniques.

The correlation of volcanic ash horizons

Bentonite horizons (also termed K-bentonites or metabentonites by some authors) result from the deposition of volcanic ash within a marine setting, and are a common feature of the Silurian of the Midland Platform (Huff *et al*. 1996). Bentonites typically consist of white, greenish-grey or rusty-orange clays (e.g. chlorite, illite, kaolinite and smectite) (Fig. 3, *overleaf*) with a minor component of volcanic phenocrysts (e.g. apatite, biotite, feldspar, quartz and zircon) (Fig. 4, *overleaf*). Individual horizons typically range in thickness between 10mm and 100mm, but occasionally exceed 500mm. Within abandoned quarries bentonites can be readily identified by bands of vegetation, which take advantage of the water that percolates along these impermeable clay-rich horizons.

Bentonites are among the most geologically important deposits to be found within the sedimentary record. In particular, the occurrence of volcanogenic minerals, such as zircon,

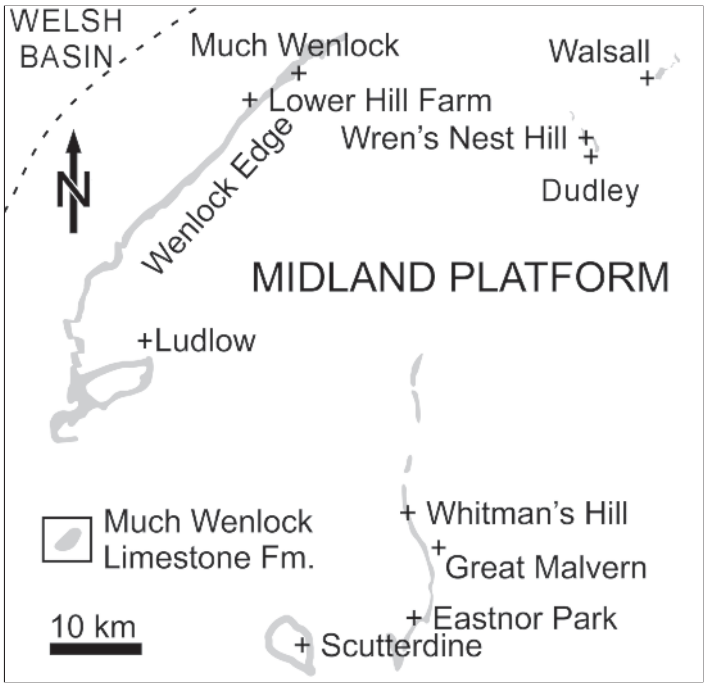


Figure 2 An outcrop map of the Much Wenlock Limestone Formation (upper Wenlock) showing the location of sections and boreholes discussed within the text.

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Figure 3 A prominent bentonite exposed high on the southern face of Whitman's Hill Quarry, Storridge (Herefordshire) — note the plant roots within the bentonite. The field notebook is 200mm high and rests directly on top of the bentonite (bentonite code WH9 in Ray et al. *2013).*

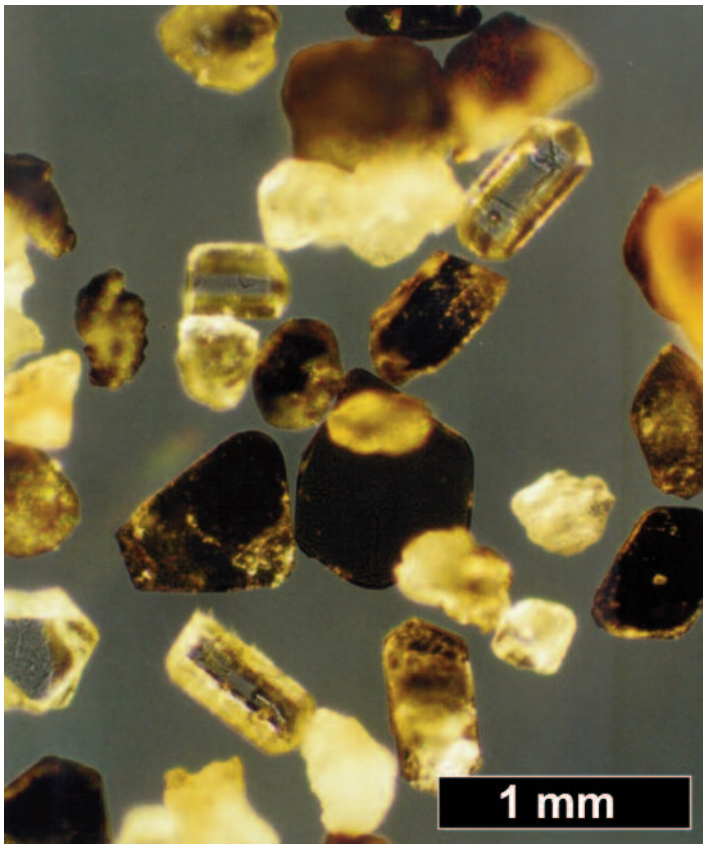
enables the absolute radiometric dating of bentonites. Thus, bentonites contribute ages expressed in millions of years to the relative age constraints (e.g. biozones) of the sedimentary record and are therefore crucial in the construction of geologic timescales. For example, a latest Wenlock bentonite collected from Wren's Nest Hill (Dudley, West Midlands) has provided an age of 427.86±0.32Ma in close proximity to the Wenlock-Ludlow series boundary (Cramer *et al.* 2012), indicating that the currently accepted age for the Wenlock-Ludlow series boundary (427.4±0.5Ma; Melchin *et al.* 2012) is a slight underestimate. In addition to providing absolute ages, bentonites can be chemically unique and result from a single large ash cloud that can be deposited extremely rapidly. Accordingly, the chemical signature of bentonites can reveal a wealth of information relating to their magmatic origin, and the identification of the same bentonite across a region can enable the establishment of a timeline that reflects the eruption event; with respect to the geologic timescale, such events are geologically instantaneous.

The Wenlock Series (433.4–427.4Ma) of the Midland Platform contains at least 150 discrete bentonite horizons, suggesting an average duration of 40,000 years between eruptions. Core and outcrop studies demonstrate a clear clustering of bentonites within lower energy, deeper-water facies (Ray and Butcher 2010). This distribution indicates that bentonite occurrence was strongly influenced by processes affecting deposition and preservation (e.g. sedimentation rate, depositional energy, bioturbation index and reworking), as well as by the frequency of eruptions. The abundance of bentonites upon the Midland Platform indicates a close proximity to one or more volcanic centres. In particular, proximal volcanic deposits (lavas and or tuffs) are reported from the East Mendips (Somerset, England), Powys (Wales) and the Dingle Peninsula (Kerry, Ireland) (Cave and Loydell 1998) (Fig. 5, *opposite*). These represent the closest known volcanic centres and, like the majority of bentonites, are of intermediate to acid composition (Huff *et al.* 1996). A more detailed assessment of compositional data indicated that volcanism results from arc to within-plate processes. Furthermore, there is a compositional evolution of the magmatic processes, with bentonites typically becoming progressively acidic within younger deposits.

Compositional differences have enabled geochemical fingerprinting of Wenlock bentonites and the correlation of three discrete volcanic horizons within parts of the succession that are poorly age constrained by biostratigraphic means. Such correlations have been based upon the rare earth element composition of volcanic apatite grains (Fig. 4), and have been used to demonstrate synchronous deposition within the Buildwas and Woolhope Limestone formations (lower Wenlock) (Ray 2007), and to improve stratigraphic resolution within the Much Wenlock Limestone Formation (upper Wenlock) (Ray *et al.* 2011; Ray *et al.* 2013) (Fig. 5).

Bentonites have proven especially helpful in the Much Wenlock Limestone Formation and have enabled the correlation of the succession at Wren's Nest Hill, Dudley (West Midlands) to Wenlock Edge (Shropshire) and the Malvern Hills (Herefordshire). Across this region, a particularly notable feature of the Much Wenlock Limestone Formation is the presence of a thick bentonite (120mm to 300mm) within the middle of the formation (Figs 3 and 7). This bentonite can be traced regionally not only by its unusual thickness, but also by its notably mafic composition. Furthermore, chemical and stratigraphic similarities with extremely thin bentonites found on the Baltic island of

Figure 4 Stereo-zoom microscope image of apatite (transparent, prismatic grains), biotite (opaque black-brown platy grains) and Fe hydroxides (brown irregular grains) from an early Wenlock bentonite collected from the Lower Hill Farm Borehole (Shropshire) (bentonite code LHF6558 in Ray 2007). This bentonite has been correlated with a bentonite in the Eastnor Park Borehole (Herefordshire), and has been used to demonstrate synchronous deposition within the Buildwas and Woolhope Limestone formations (Ray 2007).



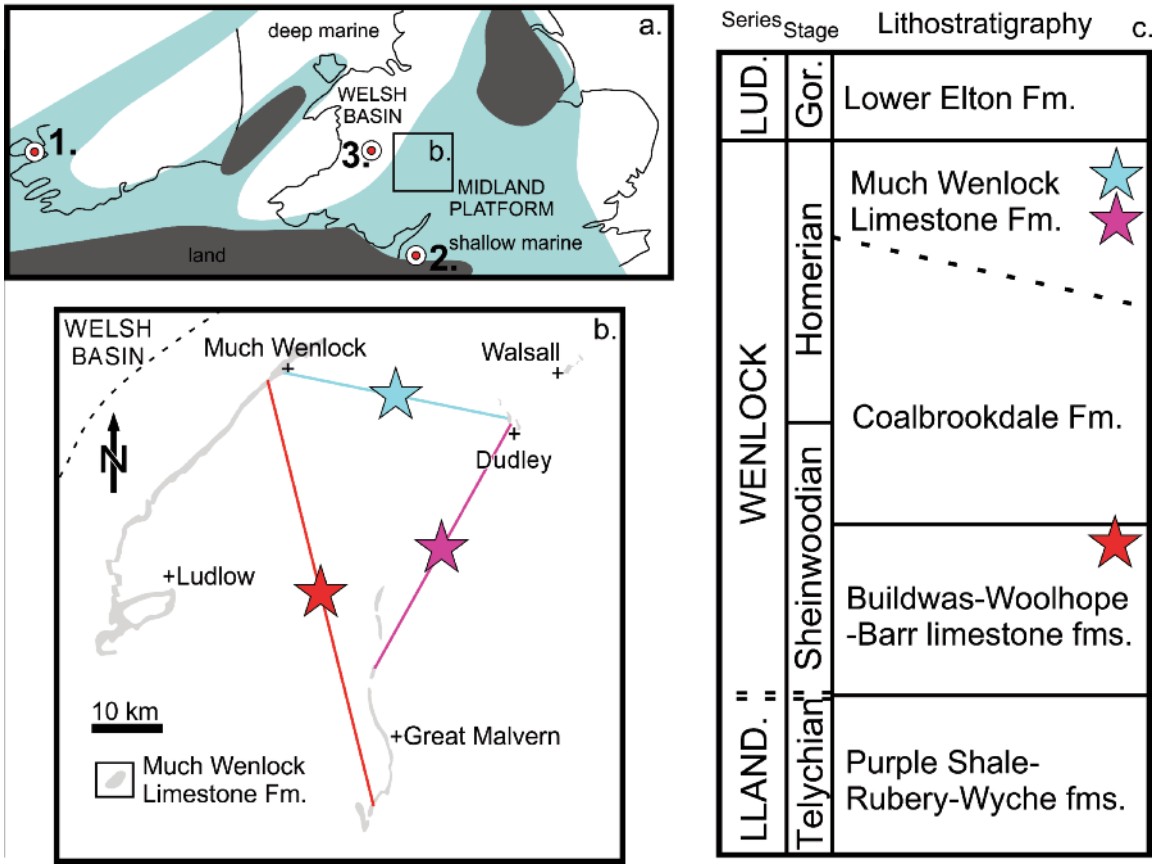


Figure 5 Palaeogeography, volcanic centers and the stratigraphic distribution of Wenlock bentonites upon the Midland Platform: a. location of the Midland Platform, Wenlock palaeogeography and nearby volcanic centers (1. Dingle Peninsula, Kerry, Ireland; 2. East Mendips, Somerset, England; 3. Powys, Wales); b. outcrop map of the upper Wenlock (Much Wenlock Limestone Formation) and the distribution of bentonite correlations across the Midland Platform (coloured lines with a star represent correlations between sections and cores). c. stratigraphic position (coloured stars) of bentonite correlations, as shown in b. (LLAND. = Llandovery; LUD. = Ludlow; Gor. = Gorstian).

Gotland (Sweden) have led to speculation that one of these bentonites corresponds to the distal edge of the same ash cloud that deposited the thick bentonite deposit across the Midland Platform (Cramer *et al.* 2012). Such a correlation would indicate an extremely large eruption that deposited ash at least 2,000km from the volcanic vent (Ray *et al.* 2013) and provide a valuable new geologic timeline.

Correlation of sea level change (sequence stratigraphy)

Sedimentary successions can be subdivided into packages relating to changes in relative sea level, and the correlation of these packages is one of the principal goals of sequence stratigraphy. These packages can be readily identified by an analysis of changes in sedimentary facies (i.e. changes in sedimentary structures, mineralogy, texture and fossil content) and, thus evidence of sea level change can be identified within many successions (Figs 6 and 7, *overleaf*). Sea level changes can be correlated at a local- to global-scale, and can take place over a range of durations (thousands to millions of years). However, the most stratigraphically useful sea level changes are those that result from short-term global processes that significantly change the volume of water within the oceans. In particular, the waxing and waning of land-grounded icecaps has the potential to change sea level globally by several tens of metres over a timescale of 100,000s of years (glacio-eustasy), thereby producing globally traceable short-duration facies changes (see Simmons 2012). The presence of icecaps at the Silurian south pole, alongside a highly variable record of global temperature change (Trotter *et al.* 2016) argues for glacial processes as the principal driver of short-term Silurian sea level change.

The Wenlock Series of the Midland Platform contains a range of frequencies and magnitudes of sea level change. At the broadest scale, sea level changes correspond well with the formations that make up the Wenlock (Ray and Butcher 2010). For example, the limestones of the lower (Barr, Buildwas, Dolyhir and Woolhope limestone formations) and upper (Much Wenlock Limestone Formation) Wenlock are reflective of relative sea level lows, while the graptolitic shales of the middle Wenlock (Coalbrookdale Formation) reflect a relative sea level high. These changes in sea level are not restricted to the Midland Platform and have been reported as synchronous events on multiple palaeocontinents. Such observations argue for global sea level change, and have enabled the construction of eustatic sea level curves (Fig. 8, *page 63*) (Johnson 2006; Melchin *et al.* 2012).

The formations of the Wenlock can be further subdivided by higher frequency changes in sea level, which can be best seen within the shallow marine limestones of the lower and upper Wenlock. These limestones can be subdivided into multiple, upward-shallowing cycles (parasequences). As these parasequences are of a scale that can be readily observed in most quarries, they represent one of the most easily identifiable and traceable features to be found within the Wenlock successions. Parasequences can be distinguished from each other and correlated according to differences in thickness and the amount of

Figure 6 Scutterdine Quarry, near Woolhope (Herefordshire): a pronounced shift in facies from shallow marine limestones (Woolhope Limestone Formation) to deeper marine shales (Coalbrookdale Formation) reflects a major sea level rise within the lower Wenlock.

relative sea level change. Furthermore, sea level trends can be observed through successive parasequences, and these stacking patterns reflect broader lithological trends that facilitate subdividing the Wenlock into members and formations.

The Much Wenlock Limestone Formation has been correlated in detail using parasequences (Ray *et al.* 2010; Ray *et al.* 2013), the synchronicity of which has been demonstrated by the correlation of bentonites (Ray *et al.* 2011; Ray *et al.* 2013). Within the West Midlands and Herefordshire, the Much Wenlock Limestone Formation can be subdivided into 12 parasequences (Fig. 7), thereby providing a considerably finer stratigraphic resolution than is achievable by the current biozonation (which is limited typically to three graptolite biozones). Furthermore, based upon the estimated duration of the Much Wenlock Limestone Formation, each parasequence (and sea level change) has a mean duration of *c.* 100,000 years, which if correct, indicates that they resulted from climate-driven sea level changes brought about by variations in the orbit of the earth (Milankovitch cycles) — akin to those that have resulted in the glacials and interglacials of the most recent geological past. At present the correlation of upper Wenlock parasequences is restricted to the Midland Platform, but if they are the result of global climate processes, they could offer the potential for high-resolution correlation with other palaeocontinents, thereby exceeding stratigraphic resolution typically provided by most biozonations.

The correlation of carbon isotopic excursions (carbon isotope stratigraphy)

Variations in the stable isotopic ratio of carbon ($^{13}C/^{12}C$ values), as measured through the stratigraphic study of marine carbonate

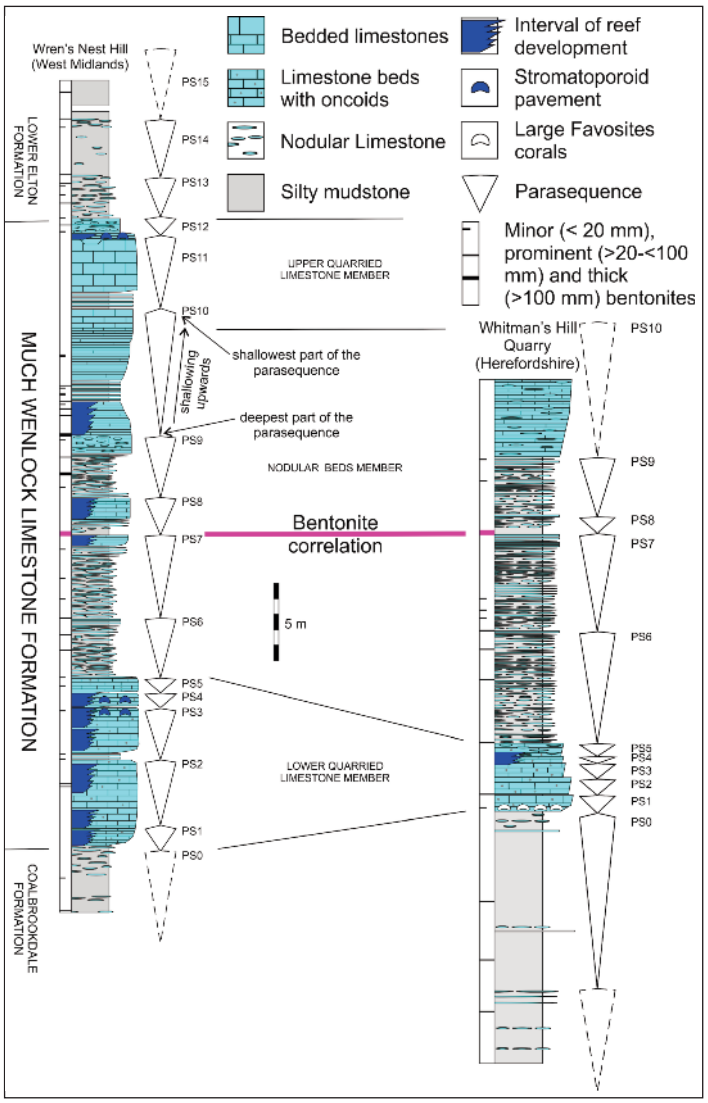


Figure 7 The correlation of parasequences within the Much Wenlock Limestone Formation (upper Wenlock) between Wren's Nest Hill (West Midlands) and Whitman's Hill Quarry (Herefordshire); note the geochemical correlation of a bentonite at the base of parasequence 8 (PS8). This bentonite correlation is shown in Figure 5 and the bentonite itself, as exposed at Whitman's Hill Quarry, is shown in Figure 3.

rocks (expressed as $\delta^{13}C_{carb}$), are related to global changes in the biosphere and carbon cycle, and as such can be used to date and correlate sedimentary successions (Saltzman and Thomas 2012). Within the Silurian this technique has proven particularly helpful in the correlation of marine successions that are lacking in age-diagnostic fossils. There are five widely recognised and pronounced changes in the stable isotopic ratio of carbon (carbon isotopic excursions) within the Silurian and these occur in the late Aeronian, early Sheinwoodian, late Homerian, mid-Ludfordian and across the Silurian-Devonian boundary (Fig. 8). A particularly notable feature of these carbon isotopic excursions is their close association with extinction events, global temperature changes and marked sea level fluctuations (Melchin *et al.* 2012; Trotter *et al.* 2016). Such a relationship indicates that carbon isotopic excursions reflect broader global changes in environmental conditions, which possibly relate to cyclic episodes of glacial advance and retreat that impacted the southern palaeocontinent of Gondwana at this time.

The Wenlock Series contains two pronounced carbon isotopic excursions (the early Sheinwoodian and late Homerian carbon isotopic excursions). These excursions have been identified in successions that contain age-diagnostic fossils on a number of different palaeocontinents (e.g. Baltica and Laurentia) and are therefore well calibrated to the geologic timescale. On the Midland Platform these carbon isotopic excursions have been used as a means of improving age calibration and correlation. In particular, the identification of carbon isotopic excursions within the Buildwas, Woolhope Limestone, Barr Limestone, Brinkmarsh Beds and Much Wenlock Limestone formations has resulted in important re-evaluations of age for these successions (e.g. Marshall *et al.* 2012; Hughes *et al.* 2014; Hughes and Ray 2016; Blain *et al.* 2016; Fry *et al.* 2017), and has greatly improved upon the age assignments achieved by biostratigraphic means alone.

An example of the application of carbon isotope stratigraphy to our understanding of the Wenlock can be taken from the type succession along Wenlock Edge (Shropshire). Here the identification of the early Sheinwoodian carbon isotopic excursion (ESCIE) within the Lower Hill Farm Borehole revealed significant problems with the established graptolite biozonation (Hughes and Ray 2016). In particular, the ESCIE did not occur within expected graptolite biozones (Fig. 9, *overleaf*), thereby suggesting that these biozones were not age-equivalent to the same biozones as reported elsewhere, which do contain the ESCIE. Most notably, elsewhere the *riccartonensis* Graptolite Biozone is consistently associated with the middle of the ESCIE (Melchin *et al.* 2012), but this biozone within the Lower Hill Farm Borehole was reported above the ESCIE and in the lowest part the Coalbrookdale Formation. An examination of the original biostratigraphic report from the borehole (Bassett 1974) revealed only a questionable identification of *Monograptus riccartonensis*, but nonetheless this biozonal age has been taken for the base of the Coalbrookdale Formation within the type-Wenlock succession and beyond (Cocks *et al.* 1992). Based on the identification of the ESCIE and the correlation of this excursion to nearby successions that contain age-diagnostic fossils (e.g. chitinozoans, conodonts and graptolites) (Hughes and Ray 2016), it is apparent that the stratigraphic position of the *riccartonensis* Graptolite Biozone should correspond to somewhere within the middle of the Buildwas Formation, rather than to the base of the overlying Coalbrookdale Formation. Thus, the age of the contact between the Coalbrookdale and Buildwas formations is younger than previously thought (equivalent to the *rigidus* Graptolite Biozone). In addition, the identification of the ESCIE in the Woolhope Limestone Formation of Herefordshire strongly suggests age equivalence with the Buildwas Formation, a view that has been additionally confirmed by bentonite and sequence stratigraphic correlations.

Conclusions

Despite being among the most intensively studied of Wenlock successions, the stratigraphic correlation of the Midland Platform has proven problematical. Limitations imposed by a rarity of age-diagnostic fossils, such as chitinozoans, conodonts and graptolites, have resulted in age and correlation uncertainties (Cocks *et al.* 1992). As a means of addressing these uncertainties, the pre-existing biostratigraphic frameworks have been supplemented in recent years by the application of other correlation techniques. In particular, the geochemical finger printing of volcanic ash bands, correlation of sea level changes, and variations in carbon isotopic record have proven crucial in increasing our stratigraphic understanding of these classic Silurian successions. Furthermore, these techniques not only offer the possibility to subdivide the rock record at an increasingly fine scale, but they inform us about the world beyond the Midland Platform and tell of ancient volcanism and plate tectonics, palaeoclimate and sea level change, and changes in Silurian life and its influence upon the carbon cycle.

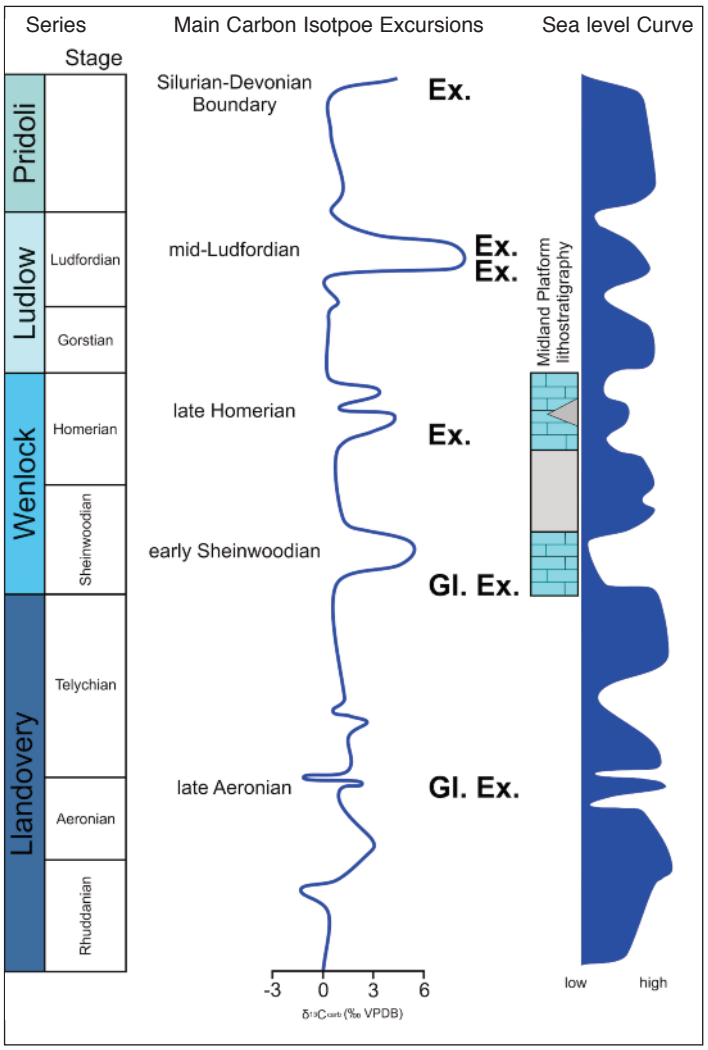


Figure 8 Series, stages and a generalised $\delta^{13}C_{carb}$ for the Silurian System, identifying the most widely recognised and pronounced carbon isotope excursions, alongside prominent extinction events (Ex.), well known glaciations (Gl.) and the global (eustatic) sea level curve of Johnson (2006) (modified from Melchin et al. *2012).*

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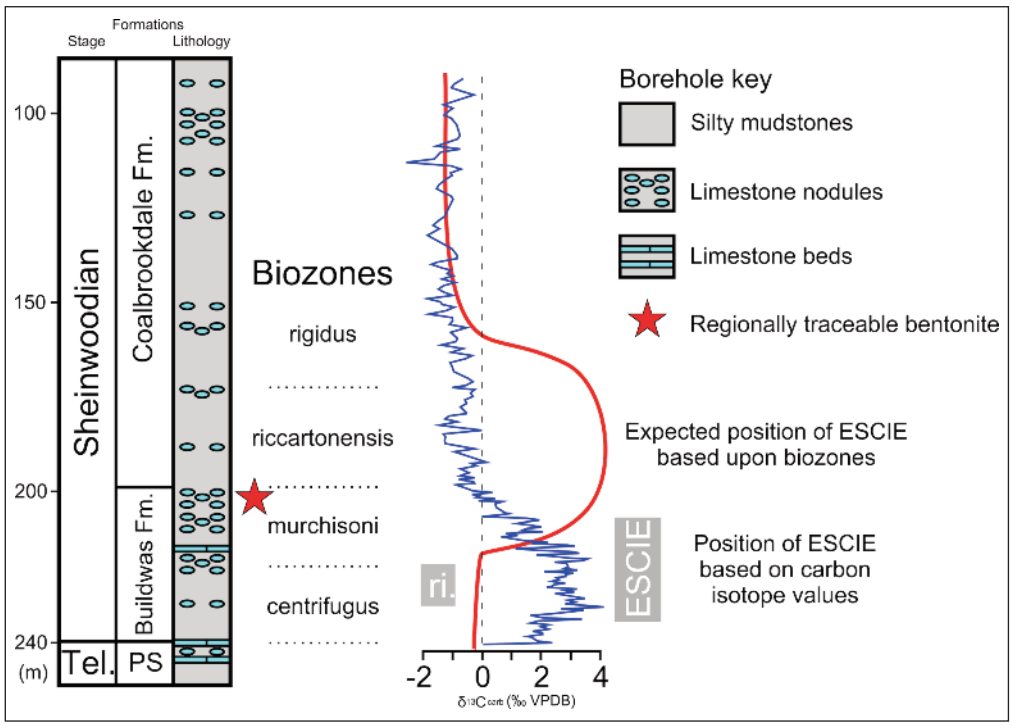

Figure 9 The stratigraphy and carbon isotopic record from the Lower Hill Farm Borehole, Shropshire (modified from Hughes and Ray 2016). Biozones are modified from Bassett (1974) and Cocks et al. *(1992). The red carbon isotopic curve represents the expected position of the Early Sheinwoodian Carbon Isotope Excursion (ESCIE) based on the established graptolite biozones. The blue carbon isotopic curve represents the isotopic values recorded by Hughes and Ray (2016). The regionally traceable bentonite (Ray 2007) is that referred to in Figures 4 and 5. ri. = the likely position of the* riccartonensis *Graptolite Biozone based upon the position of the ESCIE and additional biostratigraphic considerations.*

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The geological shaping of Wales

Nigel H. Woodcock

Department of Earth Sciences, University of Cambridge. Downing Street, Cambridge CB2 3EQ
nhw1@cam.ac.uk

Introduction

Wales contrasts with bordering England in being an upland country mostly underlain by Carboniferous or older rocks. The area of England to the east of Wales is comparatively low-lying, with Permian or younger rocks at outcrop (Fig. 1). How did these contrasts arise?

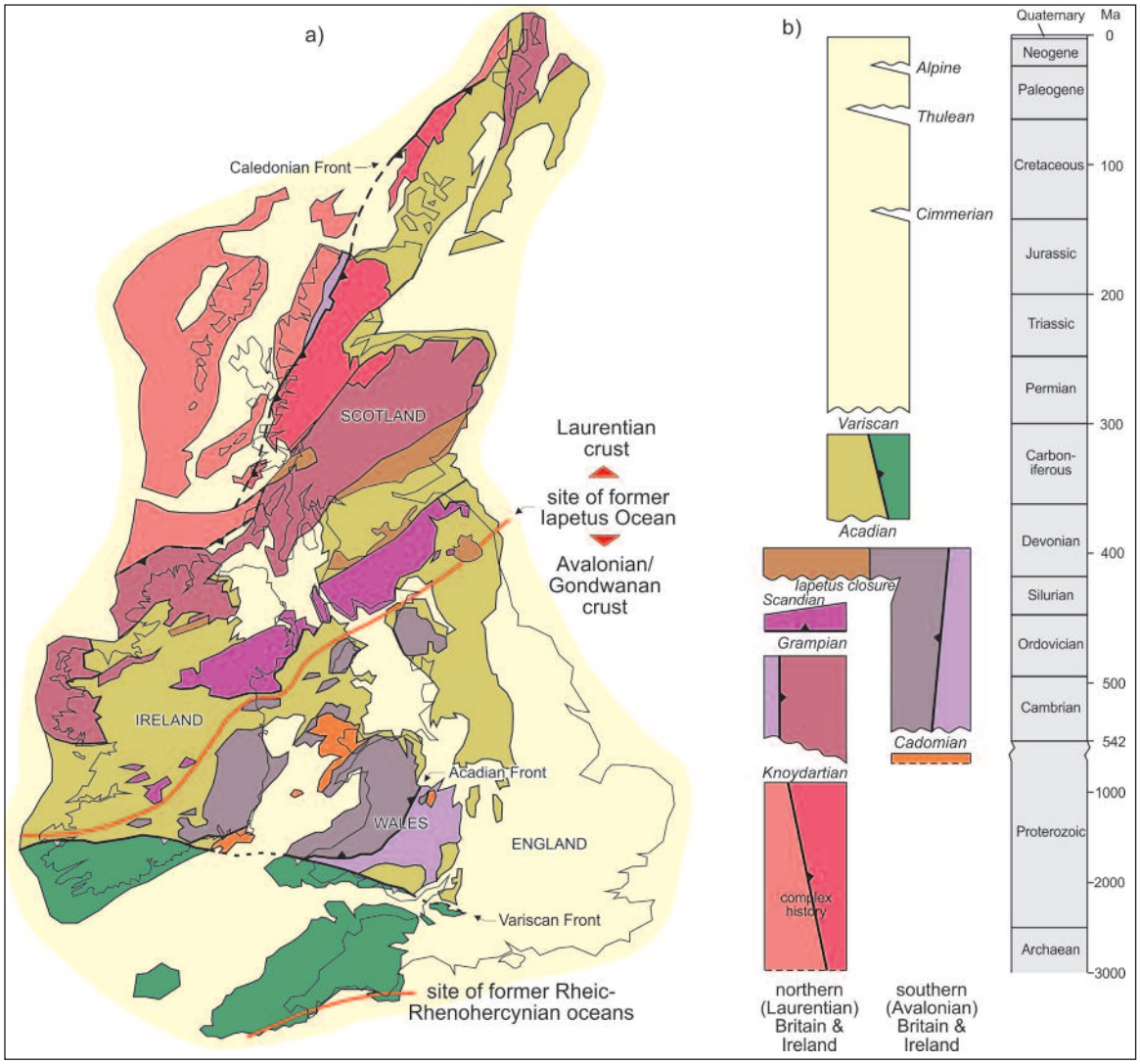
One popular view is that the Welsh hills are the remnants of the Acadian mountain belt, formed in Devonian time (Fig. 1) and not yet eroded down. This view has only an essence of truth. The pre-Late Devonian rocks that make up much of Wales were indeed folded, cleaved and weakly metamorphosed near the end of Early Devonian time, making them more compact and more resistant to erosion. But their present relief owes less to the inefficiency of post-Devonian erosion and more to three later landscape-shaping processes in the Mesozoic and Cenozoic.

Shaping process 1: Acadian and Variscan orogenies

Despite later events, the geological grain of the Welsh bedrock does date from Palaeozoic events. Most folds and, to a lesser extent, faults run from north-east to south-west, although swinging round towards east–west in north and west Wales (Fig. 2, *overleaf*). This grain results from the Acadian deformation phase in Early Devonian time and affected Wales from Anglesey in the north-west across-strike as far as the Welsh Borderland. Structural cross-sections (Fig. 3, *overleaf*) show folds of the Cambrian to Early Devonian rock sequence, cut by a cleavage that mostly dips north-westward.

The Acadian deformation gets weaker to the south-east, as it approaches a family of three parallel faults — the Severn Valley, Pontesford-Linley and Church Stretton faults — together called the Welsh Borderland Fault System. Beyond this Acadian

Figure 1 (a) Simplified geological map of Britain and Ireland; (b) key to the geological map in the form of a stratigraphic column (modified from Holdsworth et al. *2012).*



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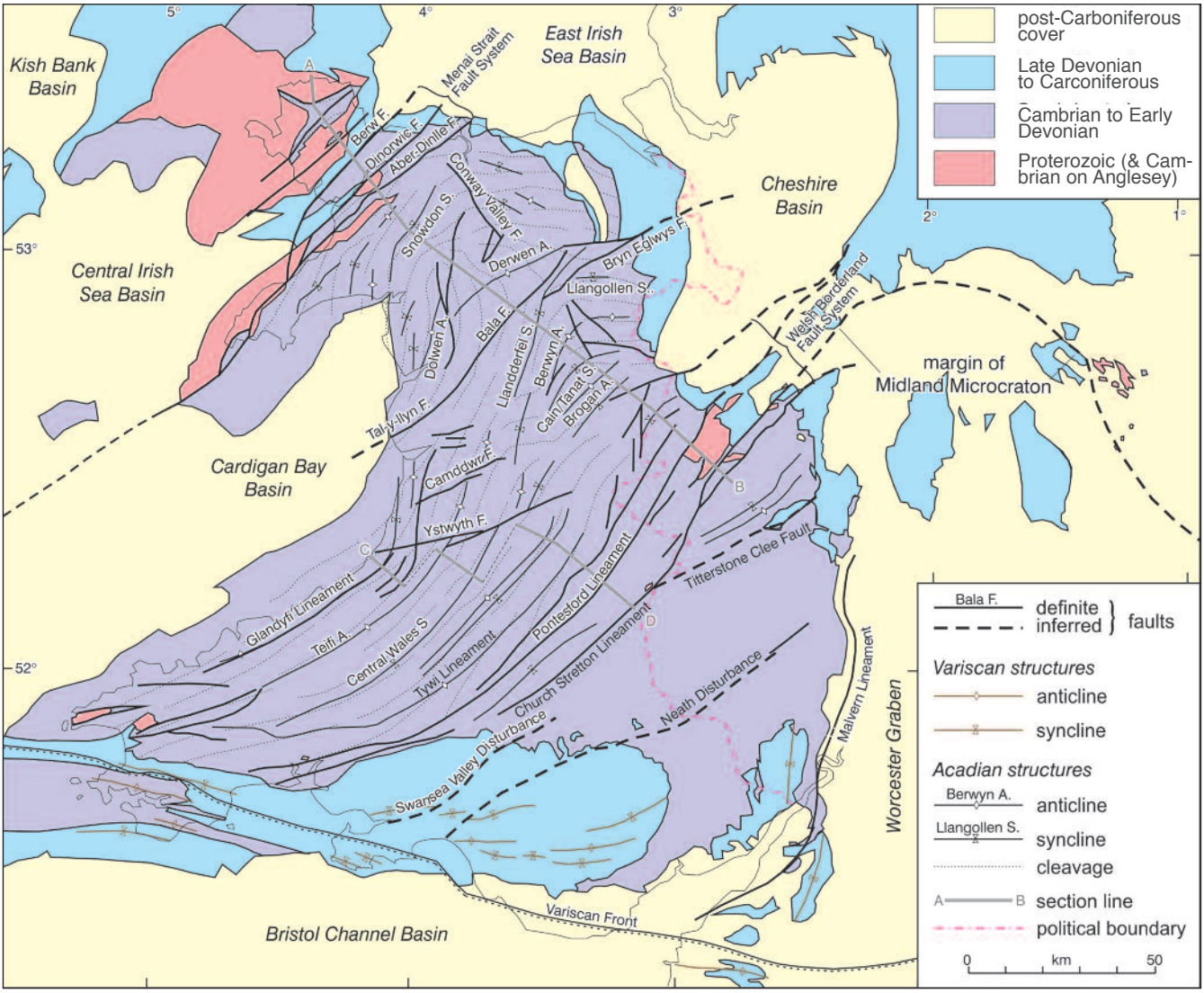
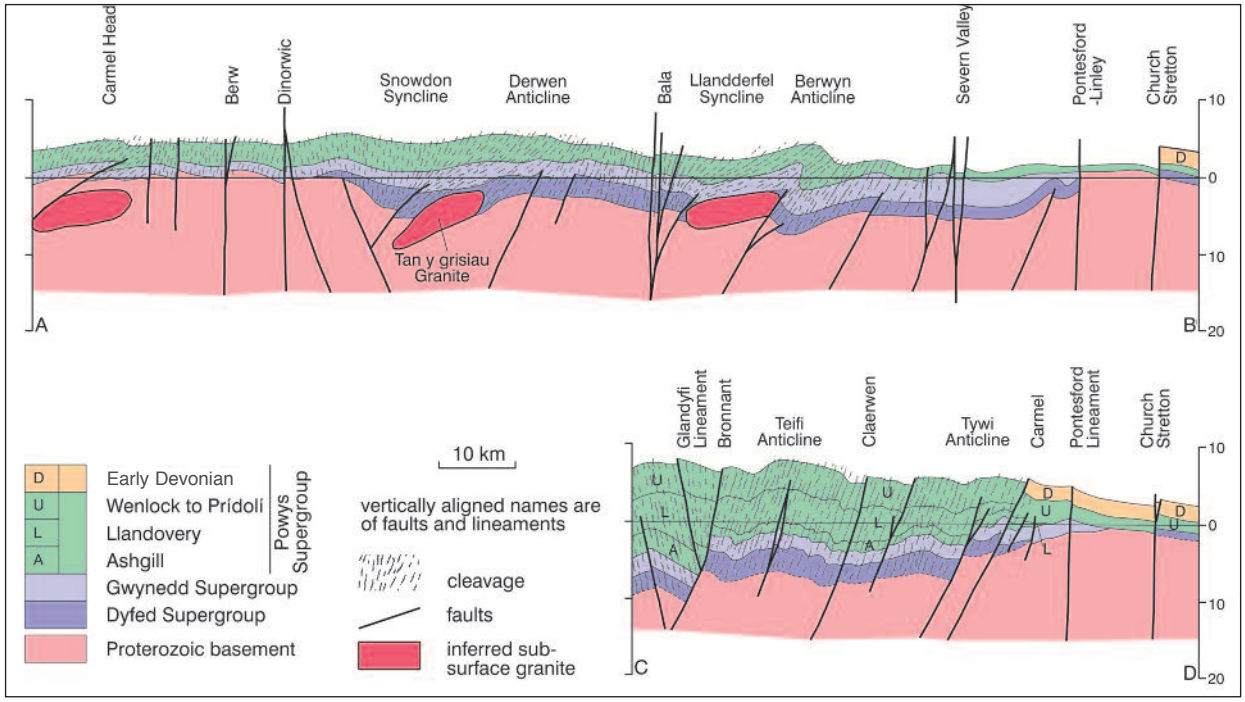


Figure 2 Geological map of Wales (amended from Woodcock and Soper 2006).

Figure 3 Structural cross-sections: (a) north Wales and (b) mid-Wales; section lines marked on Fig. 2 (modified from Woodcock and Soper 2006).



'deformation front' lie gently-dipping Early Devonian rocks overlain in turn by Late Devonian and Carboniferous rocks that post-date the Acadian deformation.

The structural grain south-east of the Acadian Front has two components. First, the Variscan deformation of Late Carboniferous age runs east–west across the south of Wales (Fig. 2). It is just the northern edge of a Himalayan-scale mountain belt that mostly lies beyond Britain. Variscan folding is strong to the south of the Variscan Front, but affects also the south Wales coalfield to the north. The second structural component is the north–south Malvern Lineament (Fig. 2), which reflects a trend in the old Proterozoic basement rocks that was reactivated during the Variscan shortening and during Mesozoic extension.

The geological limits of Wales

What is meant by Wales in a geological rather than a political sense?

On the 'Acadian remnant' view of Wales, maybe its geological boundary should be the Welsh Borderland Fault Belt (Fig. 2)? However, this 'Acadian Front' is an inappropriate choice. The large area of gently deformed rocks in south-east Wales and the contiguous Welsh Borderland are nevertheless upland terrain, showing that events other than the Acadian deformation were responsible for hilly Wales. These uplands include the south Wales coalfield, but not, paradoxically, the strongly deformed remnants of the Variscan orogeny in south Pembrokeshire and on the Gower Peninsula (Fig. 2), which are actually topographically lower than the less deformed Carboniferous rocks to the north. Again, something other than these orogenic events must be responsible for the upland nature of inland Wales.

A clue to an alternative approach to delimiting Wales geologically is that the country is almost entirely surrounded by Permian and later rocks (Fig. 2). To the north, west and south of Wales, the coastline is closely mimicked by mostly offshore boundaries between pre-Permian rocks and the Permian and later sedimentary basins. In some places, these boundaries are the sub-Permian or Triassic unconformity; in others they are normal faults that let down the basins with respect to the Welsh Massif. In two regions, geological Wales extends well offshore: on the Pembrokeshire Platform extending out from west Wales, and on the Holy Island Shelf that continues Anglesey. To the east of Wales, there are similar boundaries with Permian and later rocks: boundaries either faulted or unconformable between the Welsh Massif and the Cheshire Basin and Worcester Graben (Fig. 2).

So the geological Wales discussed in this article is not delimited by its political boundaries, but also includes south Shropshire, most of Herefordshire and the western corner of Worcestershire. This geologically colonised part of England is essentially the area covered by the old Welsh Borderland volume of the British Regional Geology series (Earp and Hains 1971). However, the more recent volume on Wales (Howells 2007) authoritatively covers the whole of geological Wales.

Shaping process 2: Permian to Early Cretaceous rifting

The geological boundaries of Wales suggest that the country was defined by extension of surrounding basins in Permian or later time. This is the second of four processes that shaped Wales into its present form.

The Pangaea supercontinent, formed by welding the northern and southern continents during the Variscan Orogeny, was beginning to break up again from Late Permian time (Fig. 4). The crust

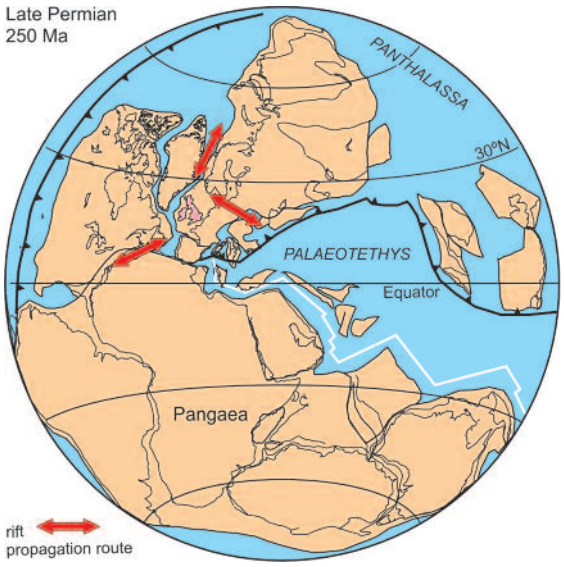


Figure 4 Palaeocontinental map showing the geological setting of Britain and Ireland as the Pangaea supercontinent began to break up; arrows show the three routes of attempted lithospheric rifting (modified from Holdsworth et al. *2012).*

around Britain and Ireland was cracking apart in rift zones propagating from three directions: from the newly forming central Atlantic, from the Tethys Ocean to the south-east, and from the future Arctic Ocean to the north (Fig. 5, *overleaf*).

Each rift zone or graben was made up of arrays of normal faults dipping inwards to an elongate rift basin, each basin flanked by upstanding horsts or massifs (Fig. 6, *overleaf*). Under the basins, the entire 100km thick lithosphere was being stretched and thinned, causing the crust to subside. By Late Triassic time, these rifts were becoming seaways and hosting marine sedimentation. By contrast, massifs like the Welsh Massif remained unstretched, so that their underlying lithosphere retained its original thickness and its surface stayed at or above sea level.

Wherever mechanically possible, the propagating rift zones followed the tectonic grain in the pre-existing continental crust. Around Wales (Fig. 5), the Celtic Sea, St George's Channel and Central Irish Sea basins followed the old north-easterly Caledonian grain. The Bristol Channel Basin diverged from this trend to follow the east–west Variscan grain, and the link through to the east–west Wessex-Weald Basin. The Palaeozoic Midland Platform, which had avoided both strong Caledonian and Variscan deformation, was now cut by the Worcester Graben that followed the northerly grain of the platform's Proterozoic basement. The Cheshire and East Irish Sea basins responded partly to this northerly grain and partly to the north-easterly Caledonian grain.

The basins surrounding Wales probably began to extend in Late Permian time (Fig. 7, *page 69*), though dating this extension accurately is difficult in rocks with few fossils. First, Wales formed rocky uplands between arid desert basins, but by Late Triassic time those basins had subsided enough to enable the sea to encircle the Welsh uplands. The unconformity between Triassic and Carboniferous rocks is still exposed in places in south Wales, preserving the onlap of basinal deposits on to the Welsh landmass (Fig. 8a, b, *page 69*). By Early Jurassic time, fully marine limestone/mudstone sequences were being deposited in the deeper basins. The shoreward edge of these sequences is exposed in south Wales (Fig. 8c).

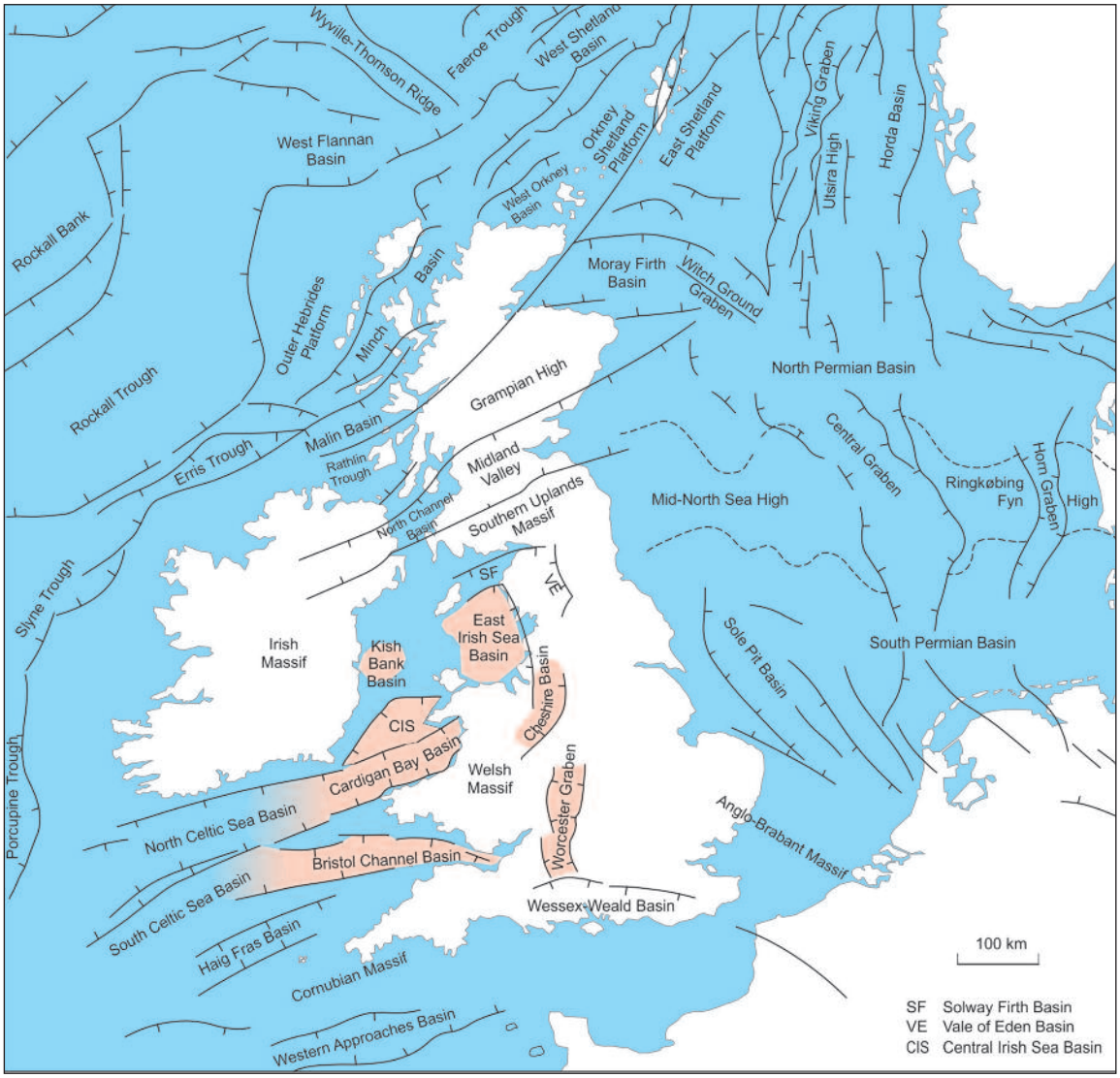
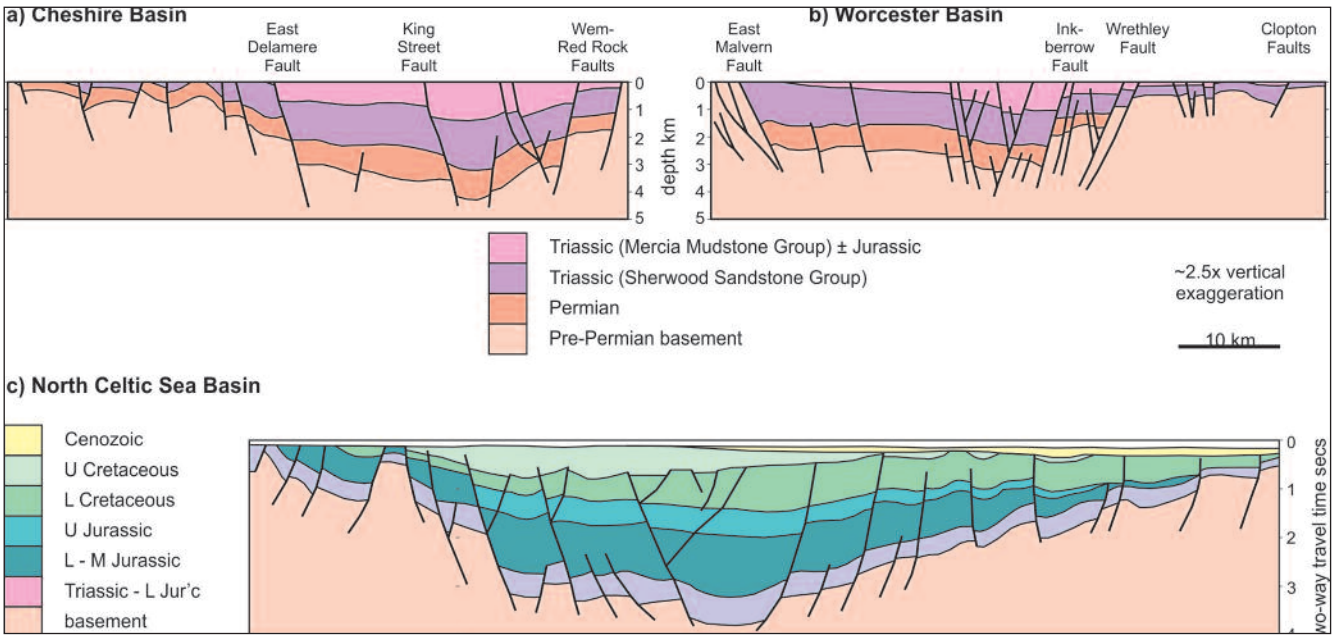


Figure 5 Map of the main Mesozoic to Recent sedimentary basins around Britain and Ireland: basins surrounding Wales are highlighted (modified from Holdsworth et al. *2012).*

Figure 6 Sections across typical Mesozoic basins surrounding Wales: (a and b) Worcester and Cheshire basins (modified from Chadwick and Evans 1995); (c) north Celtic Sea Basin (modified from Tucker and Arter 1987).



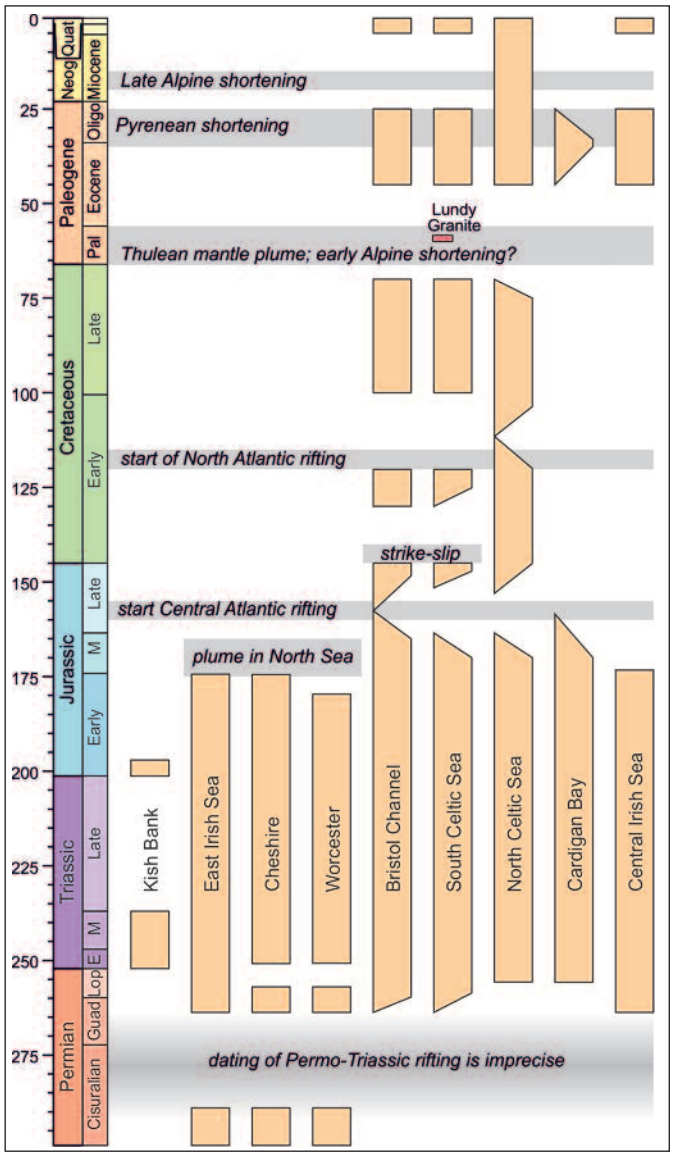


Figure 7 Summary stratigraphic logs of the Mesozoic basins around Wales, showing the preserved rock units and the relevant tectonic rifting and uplift events: columns based on data in Knipe et al. *1993, for east Irish Sea; in Chadwick and Evans 1995, for Cheshire and Worcester; in Kamerling 1979, for Bristol Channel; in Van Hoorn 1987, for south Celtic Sea and Bristol Channel; in Tucker and Arter 1987, for north Celtic Sea and St George's Channel; in Floodpage* et al. *2001, for central and east Irish Sea; and in Izatt* et al. *2001, for central Irish Sea.*

Crustal extension continued through Jurassic time causing normal faults to cut already deposited Jurassic rocks in places (Fig. 8d). On seismic profiles, arrays of these normal faults dip inwards towards the basin centre to form a graben with the greatest sediment thickness in the centre (Fig. 6). In a textbook extensional basin this normal faulting and extensional subsidence would have ended and the basin would have continued to subside only gently in response to cooling of the stretched continental lithosphere. However, in all the basins surrounding Wales, gentle subsidence was interrupted in the Middle Jurassic to Early Cretaceous by non-deposition or uplift events (Fig. 7).

Permian to Recent stratigraphic columns (Fig. 7) show two main sorts of depositional record in the basins around Wales. In those to the north and east (Kish Bank, east Irish Sea, Cheshire, Worcester) no substantial deposits are preserved later than the Middle Jurassic. If later deposits did accumulate, they were later uplifted and eroded. The basins around the south and west of Wales (Bristol Channel, south and north Celtic Sea, Cardigan Bay) do preserve post-Middle Jurassic rocks, but in short sequences separated from each other by gaps in time — leaving unconformities.

These time gaps, as many as five in total, suggest that non-deposition or erosion occurred around Wales not just once but repeatedly: one event in the Late Jurassic, two in the Early Cretaceous, one early in the Paleogene and one in the Neogene. Vitrinite reflectivity and fission track dating of apatite (Holford *et al.* 2005, 2009) clarify that each of these events was associated with

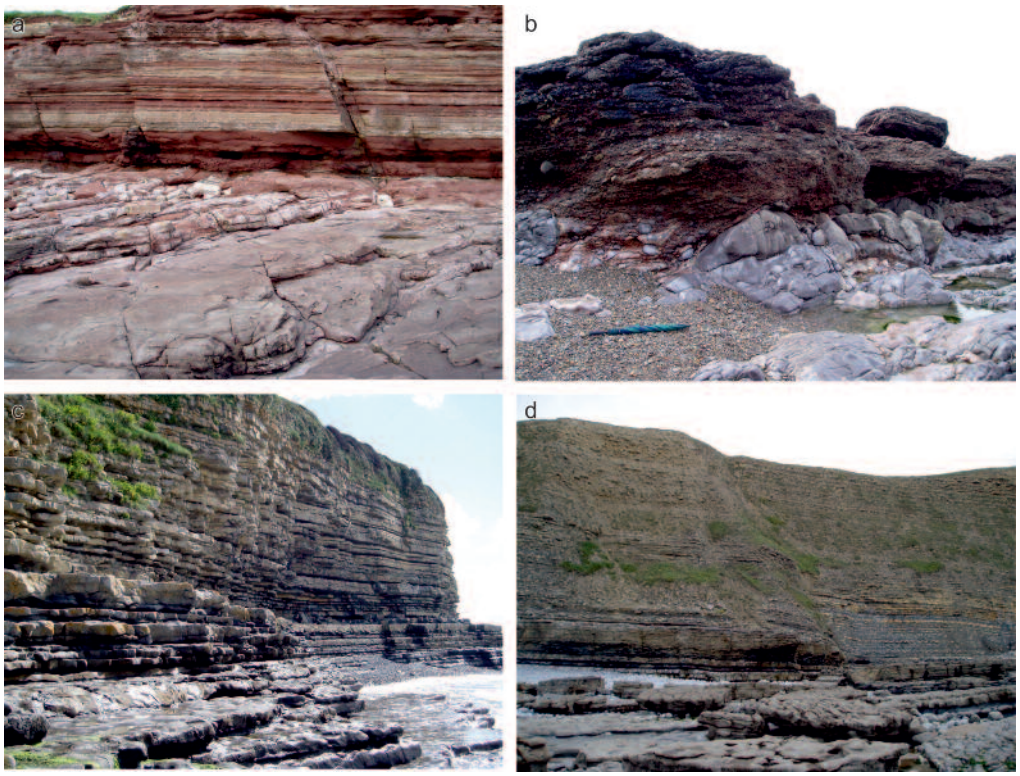


Figure 8 Photos from the margin of the Bristol Channel Basin in Glamorgan:

(a) Triassic Mercia Mudstone Formation marginal marine sediments unconformably overlie Early Carboniferous limestones, Bendrick Point;
(b) Triassic wadi-fill conglomerates unconformably overlie deformed Early Carboniferous limestones, Ogmore-by-Sea;
(c) Lias Group (Early Jurassic) marine limestone and mudstone, Ffontygari Bay; and
(d) Normal fault cuts Lias Group limestone and mudstone, Dunraven Bay.

active uplift, partially reversing the earlier subsidence and enabling the upper parts of the basin fill to be eroded by subaerial processes. In between uplift events, the Celtic Sea and the Bristol Channel basins at least continued to subside and accumulate sediment, particularly during the Late Cretaceous and Late Paleogene.

The cause of the Late Jurassic and Early Cretaceous events is uncertain. The Late Jurassic event coincides with the onset of rifting in the Central Atlantic and the Aptian (Early Cretaceous) event with the start of rifting in the Bay of Biscay and North Atlantic (Doré *et al.* 1999). The earliest Cretaceous event has been attributed to major strike-slip faulting in the south Celtic Sea and the Bristol Channel basins (Van Hoorn 1987).

Shaping process 3: Cenozoic uplift events

A third influence on the making of Wales were uplift events in the Early Paleogene and Early Neogene. The first of these events was magmatic rather than tectonic: the onset of a mantle plume beneath north and west Britain and Ireland in the Paleocene, just at the time when the North Atlantic Ocean was beginning to form. A schematic cross-section through this plume (Fig. 9) shows how hot upwelling of mantle impinged on the lithosphere and spread laterally beneath it on either side of the incipient ocean. One consequence of this spreading plume was partial melting of some of the rising mantle, fuelling the well-known igneous activity in north-west Britain (Fig. 10). A second consequence was the heating of the lithosphere beneath Scotland, Ireland, Wales and northern England, causing thermal expansion and uplift. This was followed by permanent addition and solidification of mafic magma below the continental crust. This magmatic underplating meant that the uplift did not decay through time, but that a large area of north-west Britain was permanently uplifted (Fig. 10).

The Paleocene uplift affected the old Mesozoic basins around Wales as well as the Welsh Massif itself. Even the basins to the south and west of Wales show an unconformity at this time (Fig. 7), with sedimentation resuming in the Eocene as thermal relaxation enabled subsidence and reestablishment of marine conditions.

The Paleocene uplift event was not the last to affect Wales. Several authors, notably Brown (1960) have noticed a series of sub-horizontal erosion surfaces across the Welsh landscape. One hypothesis is that these surfaces were once at or close to sea level and have subsequently been uplifted though not deformed. Rowberry (2008) used GIS software to identify these erosion surfaces at 40–90m, 118–132m, 173–187m, 219–229m, and 385–520m above sea level.

Dating these surfaces is problematic. Brown (1960) regarded them as Neogene, but the only evidence is truncation of Oligocene clays by the lowest of these

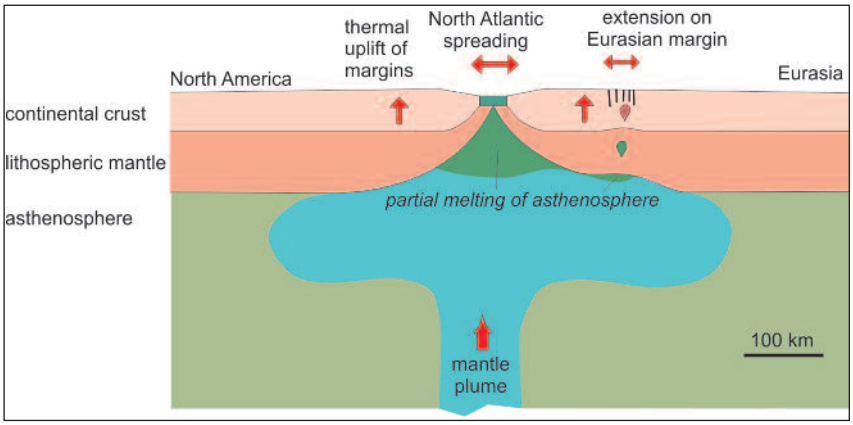
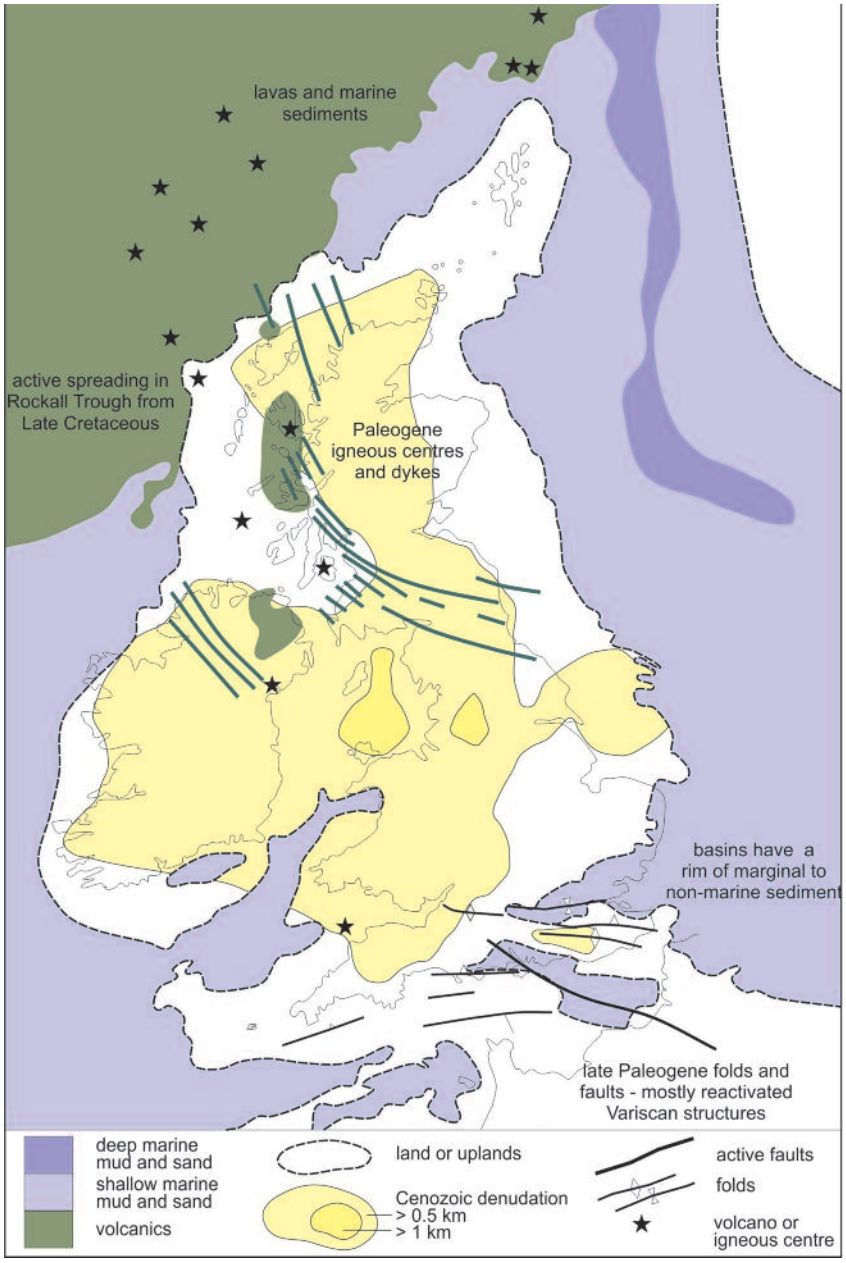


Figure 9 Diagrammatic section across the incipient North Atlantic during the Paleogene, showing a mantle plume beneath the ridge axis and spreading out beneath the bordering continental margins (modified from Gale et al. *2012).*

Figure 10 Palaeogeographic map of Britain and Ireland showing selected Paleogene igneous features and the minimum extent of Paleogene uplift and denudation (from Jones et al. *2002, fig. 4a).*


lavas and marine sediments
active spreading in Rockall Trough from Late Cretaceous
Paleogene igneous centres and dykes
basins have a rim of marginal to non-marine sediment
late Paleogene folds and faults - mostly reactivated Variscan structures
deep marine mud and sand
shallow marine mud and sand
volcanics
land or uplands
Cenozoic denudation
> 0.5 km
> 1 km
active faults
folds
volcano or igneous centre

surfaces in Pembrokeshire. The cause of their uplift is also debated, but most likely is the regional compression between the spreading Atlantic ridge to the north-west and the Pyrenean (Oligocene) and Alpine (Miocene) mountain building to the south-east.

Shaping process 4: Quaternary glaciation

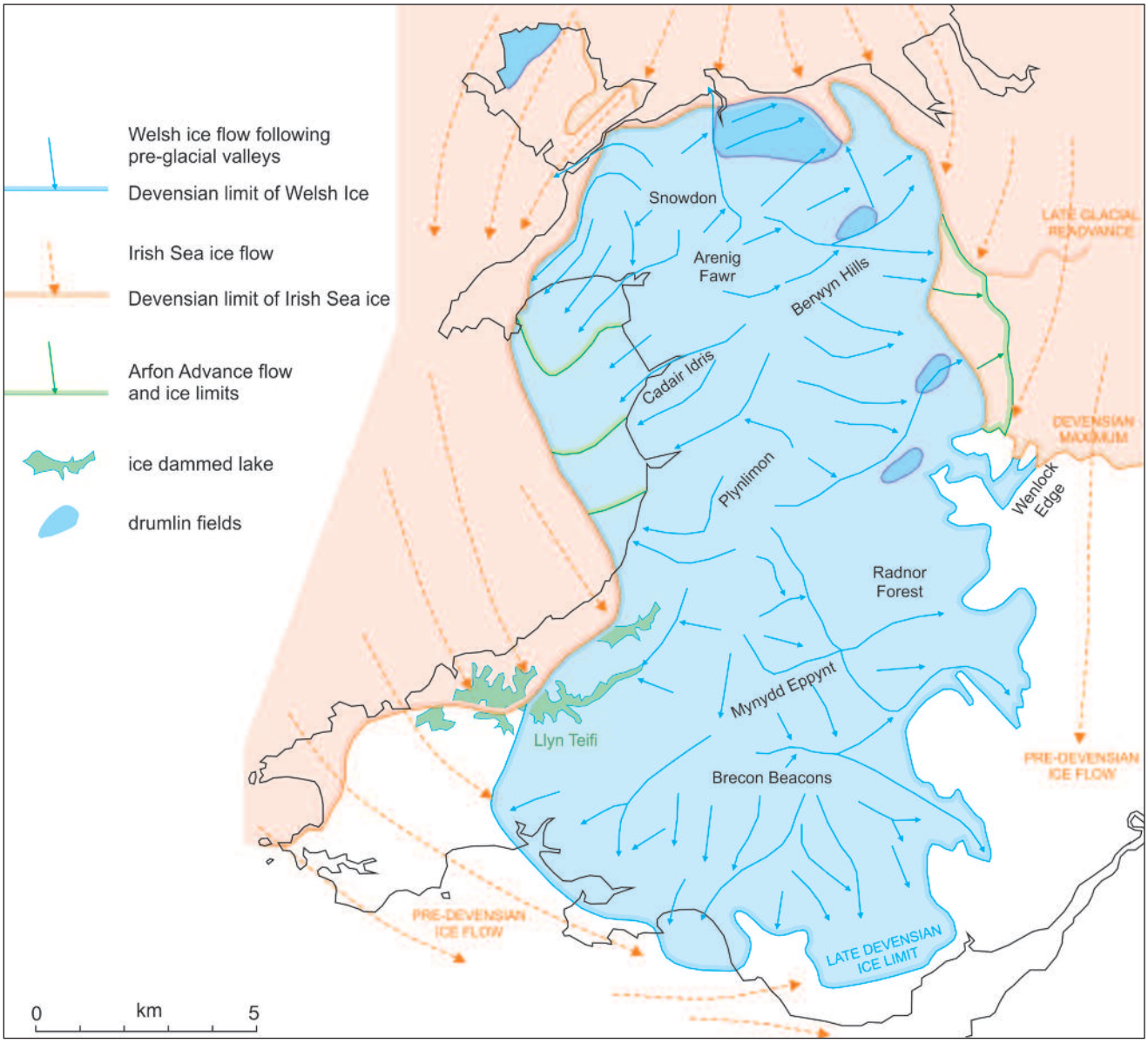
The Neogene uplift left a Welsh massif with much the same extent as that of the present day, but with a topography sculpted only by rivers dissecting the upland plateaus. However, as climate cooled into the Quaternary, those Welsh uplands provided the nucleus for the most southerly ice cap in Britain and Ireland. Ice flowed westward and eastward off the spine of Wales (Fig. 11), carrying eroded debris down into moraines around the upland fringe. In south Wales, the ice flow was southwards more or less to the present coastline, the most southerly extent of ice in on-land Britain. In north Wales, a matching northward ice flow was resisted by the strong southward advance of the large Irish Sea ice sheet.

Quaternary erosion in the hard Cambrian–Ordovician rocks of north Wales created textbook glacial features of cwms, arêtes, trim lines, U-shaped valleys, roches moutonnées, striations and hanging valleys. In the softer Late Ordovician and later rocks of mid- to south Wales, the glacial effects are more subdued, valley glaciers modifying the profiles of the pre-glacial river valleys but leaving the dissected upland plateaus more evident.

Summary

This article has explained how the geological character of Wales is only partly the result of the Palaeozoic events that formed most of its bedrock geology. The outline of Wales originates more from Permian–Triassic rifting of the sedimentary basins that surround the country. Once regional extension had finished in Early Cretaceous time, Welsh topography was further influenced by uplift events, not least a Paleocene mantle plume and Oligocene–Miocene regional compression. The resulting Welsh uplands then formed a template for the Quaternary ice sheets that sculpted the present glacial landforms.

Figure 11 Map of Wales showing the extent of the Quaternary ice sheets from the Irish Sea Ice and from the independent Welsh Ice (modified from Howells 2007).



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The Triassic rise of dinosaurs

Prof. Richard Butler

University of Birmingham

[Editor's note: Prof. Butler's article is a transcription of our recording of his lecture at the 2018 OUGS Symposium, edited for easier reading, and with selected figures from Prof. Butler. Editorial interpolations are in square brackets [ ]. The Editor would like to thank OUGS Secretary Don Cameron and Prof. Butler for their help and advice on the text and figures.]

I am going to [talk] about research [in the southern hemisphere] that we have been conducting at the University of Birmingham in collaboration with a broad range of international researchers, and at the end I will come back to some of the local relevance of this work.

Dinosaurs are a hugely successful and diverse group of animals; we are currently in a golden era of dinosaur discovery, where we are discovering perhaps a new dinosaur species every week or so. Those dinosaurs that we know already are hugely diverse in terms of their body sizes and morphologies. They range from tiny little dinosaurs weighing just a few kilos that could more or less sit on the palm of your hand, up to giant, long-necked sauropod dinosaurs weighing up to 80 tons or more in body mass. There are lots of familiar bizarre morphologies that we see within the group, from plated dinosaurs, the stegosaurs, to the giant predatory dinosaurs like *Tyrannosaurus rex*.

This is a hugely diverse and successful radiation of fossil animals[, which] were around through the Mesozoic, from *c.* 240 million years ago through to the end of the Cretaceous 65 million years ago, and we see dramatic changes in the dinosaur faunas that we see on land through that time interval. In the Triassic we have the earliest dinosaurs, which are typically very small animals like *Coelophysis*. The Jurassic is characterised by some of the really classic dinosaur faunas: animals like *Diplodocus*, *Brontosaurus*, *Stegosaurus* and so on, and then right at the end of the Cretaceous, animals like *Tyrannosaurus rex* and *Triceratops*. I am interested in [the] early part of dinosaur evolution, right at the [beginning of] the Triassic Period.

We have known about dinosaurs, of course, for a long time. The word 'dinosaur' was created in 1842 by the great Victorian comparative anatomist Richard Owen. He also commissioned the first ever life reconstructions of dinosaurs, [which] were created immediately after the Great Exhibition of 1851 when the Crystal Palace was moved to south London [and can still be seen there]. When he was working with very fragmentary fossil material at the beginning of the 19th century, o]ne of the things that Owen recognised was distinct about dinosaurs and was the basis for him erecting this new group of fossil reptiles, [was that they had a very different style of anatomy, particularly relating to the limbs,] completely different from any other group of fossil or living reptiles. [This distinction] is still very important if we are trying to distinguish dinosaurs from other groups of fossil reptiles in the Mesozoic, [and it] is that they walk with their limbs tucked underneath the body [— that is, the hind limbs of a dinosaur are held vertically underneath the body like pillars.]

That is different from [the way] crocodiles, lizards, turtles, [and other] typical reptiles hold their limbs: they hold their limbs splayed out to the side of the body, and their bod[ies] twist from side to side as they walk. Dinosaurs are much more like mammals or birds. They walk with these limbs tucked underneath the body, just mov[ing their limbs] backwards and forwards as they walk; and this is a much more efficient way of moving. This [distinctive posture compared to other groups of reptiles] is still one of the things that we use to characterise dinosaurs today.

In terms of where dinosaurs fit into the broader tree of evolution of true vertebrates, dinosaurs belong to a group that we call the 'archosaurs', the ruling reptiles[, which] include, among modern animals, the birds. So birds are the living descendants of dinosaurs, with something like 10,000 living species; but archosaurs also include the crocodiles — the crocodilians — which have many fewer species, only somewhere around 20 to 25 living species; and they are the closest living relatives of birds. This group, Archosauria, includes crocodilians [and] birds, as well as dinosaurs and a whole range of other extinct animals.

Within [the] group Archosauria there are two great evolutionary lineages: there is a lineage that leads towards the crocodilians — called Pseudosuchia; and there is [the] lineage [that] leads towards dinosaurs, and ultimately towards birds. This [group] has a difficult-to-pronounce and unnecessarily complicated name: Avemetatarsalia, which means 'bird feet' — the bird feet archosaurs. Within the Avemetatarsalia we have the flying reptiles, the pterosaurs; the dinosaurs and the birds; and some other groups that were around during the Triassic Period [and] are similar to dinosaurs in lots of ways, but do not have all of the distinctive characters of dinosaurs. [This last group is called the] 'dinosauromorphs' — almost dinosaurs, but not quite there.

I am interested not only [in] understanding the origins of dinosaurs, but [also in] this broader lineage [to] which dinosaurs belong. I am interested in understanding where this lineage comes from.

If you are interested in the origin of dinosaurs, you are interested in the Triassic: [covering the period] from *c.* 252 to *c.* 201 million years ago. It is [divided] into the Lower, Middle and Upper Triassic [or Early, Middle and Late]. One of the big stories of the Triassic for vertebrate palaeontologists is that we go from Permian ecosystems that are dominated by groups that look like this *[showing a slide]*, an animal called a gorgonopsian, which is actually on the ancestral lineage of mammals, so it is not a dinosaur. [This group was] dominant in the Permian, [but] then suffer[ed] an extinction at the end of the Permian. Then, by the end of the Triassic, you have dinosaurs and their close relatives within the Archosauria [as] the dominant land vertebrates. [As a result,] much of the story of the Triassic, for a vertebrate palaeontologist, is understanding this transition between these two major groups — mammalian ancestors, which are so important in the Permian, and dinosaurs and their close-relatives, which are so important by the end of the Triassic.

[We all know that there was a mass extinction at the end of the Permian Period. The mass extinction] at the end of the Permian, 252 million years ago, [was] the most severe in the history of life — perhaps 90% or more of species going extinct. We have no dinosaurs [before this] extinction; and the dinosaur

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lineage really start[ed] to take off in the aftermath of the Permian/end-Permian extinction.

[The extinction was] primarily caused by massive flood volcanism in Siberia, or what is now Siberia. In the aftermath of the extinction event we have [a] strange low-diversity fauna in the very earliest part of the Triassic, [for example] this animal, called *Lystrosaurus*, which we find everywhere in the world in the earliest part of the Triassic. *Lystrosaurus* is not a dinosaur; [rather, it] is one of the early mammal relatives, but it seems to be superabundant after [the Permian] mass extinction. [Specimens have been found in] Early Triassic rocks in South Africa, China [and] India.

By a few million years after the extinction [event], as ecosystems start to recover, by *c.* 247–248 million years ago, we find the first fossils of [the] group Archosauria, the group to which dinosaurs belong. The oldest known fossil of [this] group is from the latest Early Triassic in Germany — an animal called *Ctenosauriscus* (Fig. 1). The fossil material [is] embedded in the wall of the geological museum [near] Göttingen. [The fossil comprises] a series of vertebrae of the neck [with enormous long neural spines on them], the backbone and part of the tail. This is an animal that had a sail along its back, the significance of which we do not know. *Ctenosauriscus* is the earliest [known] member of the group that ultimately gives rise to dinosaurs. [It is dated *c.*] five million years after the [Permian] mass extinction, [at] the end of the Early Triassic.

If we jump forward in time [about 17 million years, to *c.*] 230 million years ago, to the beginning of the Late Triassic, we have undoubted dinosaurs present. These [early dinosaur fossils] are found particularly in the Ischigualasto Formation in Argentina,

Figure 1 Fossil material of Ctenosauriscus *embedded in wall of museum in Gottingen (photo by Richard Butler).*

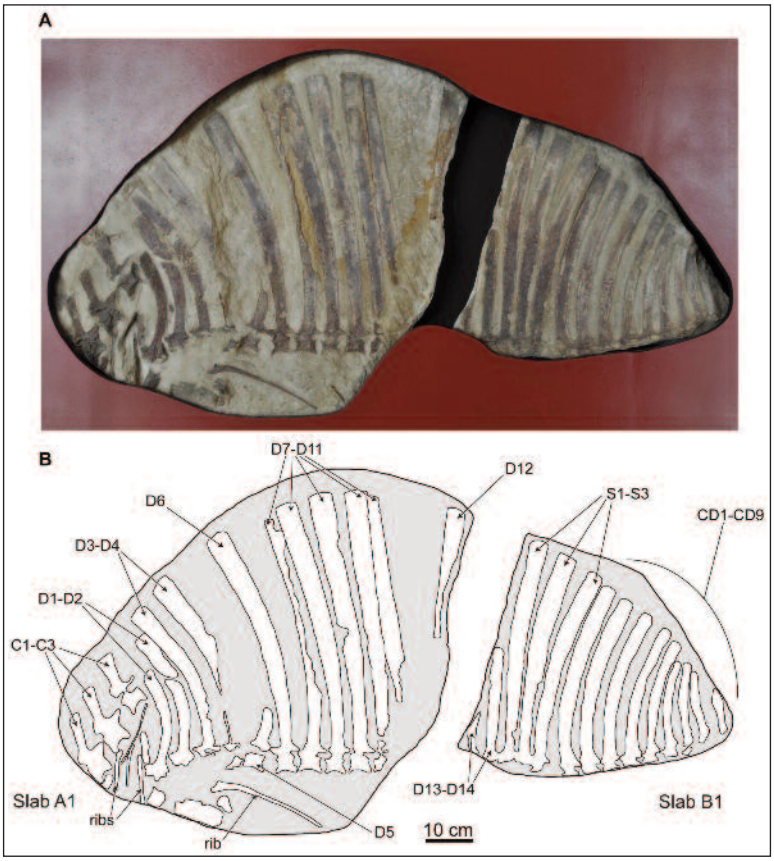


*Figure 2 Scientists excavating the remains of T*eleocrater rhadinus *and other animals in southern Tanzania in 2015 (photo by Roger Smith, reproduced with permission).*

[outcropping] in the beautiful badlands [of] western Argentina. Palaeontologists have been collecting fossils from there for a long time, and they have been finding amazing specimens of [animals] that are undoubtedly dinosaurs.

[For example,] this animal called *Herrerasaurus* — without question an early dinosaur. [It was *c.* 3–5m long] and [was probably] an early member of the theropod lineage, the lineage that gives rise to animals like *Tyrannosaurus rex*, and ultimately to birds.

What that means is that we have the earliest representatives of Archosauria at the end of the Early Triassic, and we have the earliest true dinosaurs somewhere in the Carnian [Stage,] at the beginning of the Late Triassic. So if we are interested in understanding the origins of dinosaurs, we really have to focus on the Middle Triassic, [in particular on] the Anisian and the Ladinian stages of the Middle Triassic; and that is [the period on which] I do most of my fieldwork and most of my museum-based collections research, focusing on specimens that come from this period of geological history, [dating *c.*] 247 to 235 million years ago.

One of the areas I have been most interested in is the Ruhuhu Basin of south-west [corner of] Tanzania. Palaeontologists have been collecting fossils [in this region] for quite a long time. *[Here Prof. Butler showed a palaeogeographical slide of the single supercontinent of Pangaea in the Triassic Period, indicating that at that time Tanzania was within the southern hemisphere.]* The first expeditions [to this region] were in the 1930s by University of Cambridge palaeontologists; in the 1960s, University of London and Natural History Museum palaeontologists excavated more fossils from the same horizons in south-west Tanzania; and [in the past five years] colleagues from the USA and South Africa have been working there [and] collecting new material (Fig. 2). [These collections] come from a rock unit called the Manda Beds, and most of the fossils have ended up in the collections in Cambridge and in London; and some of them have been studied in detail, [but many remained little studied] until recently: [I will describe this latter group now] (Fig. 3, *opposite*).

The stratigraphy of the Manda Beds [comprises] two distinct members: the upper member, the Lifua Member, has all of the fossils within it. There are two layers or levels within the Lifua Member that yield vertebrate fossils: an older level[, from which come] most of [the fossils] I am going to talk about; [and a] younger level, which has a more diverse vertebrate fauna. Both of these different vertebrate faunas are believed to be

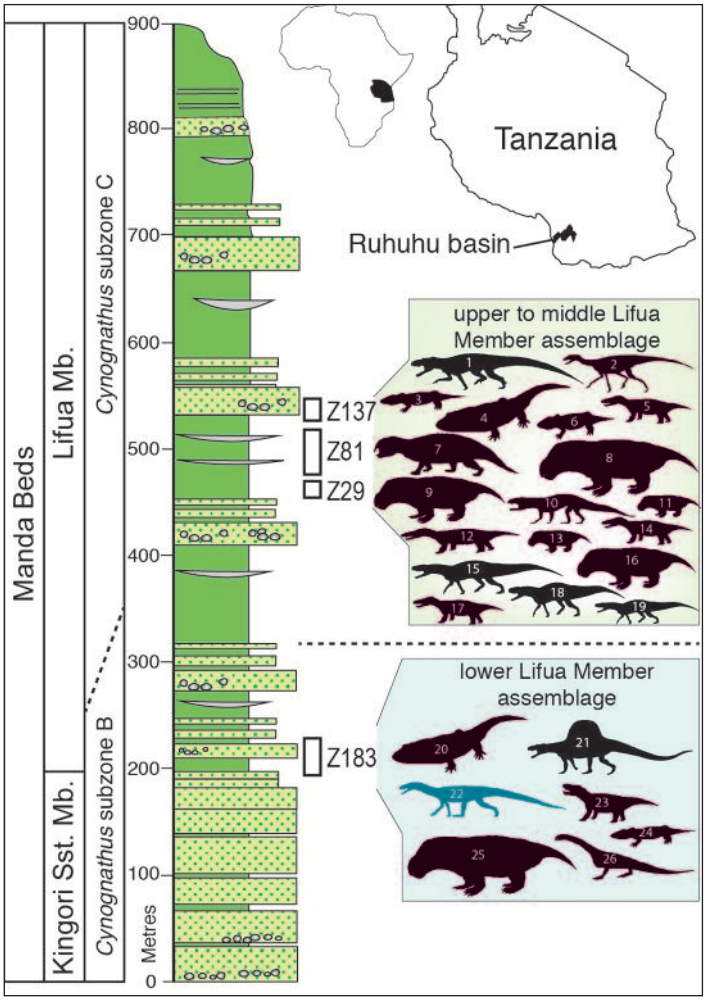


Figure 3 Stratigraphy of the Manda Beds (reproduced, with permission, from Nesbitt, Sterling J., Butler, Richard J., Ezcurra, Martín D., Barrett, Paul M., Stocker, Michelle R., Angielczyk, Kenneth D., Smith, Roger M. H., Sidor, Christian A., Niedzwiedzki, Grzegorz, Sennikov, Andrey G., and Charig, Alan J. 2017 'The earliest bird-line archosaurs and the assembly of the dinosaur body plan'. Nature ***544****, 484–7 [27 April 2017]).*

Anisian in age, so the early part of the Middle Triassic. Obviously [the lower level] is probably closer to the base of the Anisian [rocks], and is believed to be older. Unfortunately, the dating of this unit is poor. It is primarily based on vertebrate biostratigraphy, which has notorious problems, and as of yet, we have not got any radioisotopic dates for the unit.

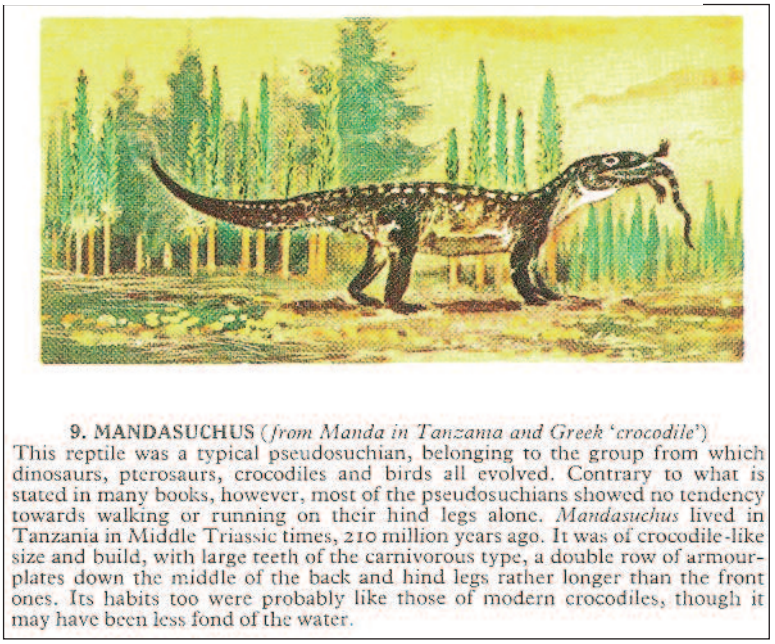
There is a diverse set of vertebrates that come from the Manda Beds, but I am interested in the archosaurs, the group that includes dinosaurs. [Archosauria] were actually studied first in the 1950s by Alan Charig, for his PhD at the University of Cambridge. Alan Charig was a well-known palaeontologist, the dinosaur expert at the Natural History Museum from the 1970s through to the 1990s, where he moved after he completed his PhD at Cambridge. [For his PhD,] he worked on some of the material [from Tanzania] that had been collected in the 1930s, and recognised [that] within this material there were new species, which are probably quite important for understanding the origin of dinosaurs. His thesis, unfortunately, was difficult to get hold of for a long time, and he never published any of this material from his thesis. So although he always intended to publish this [material], [he] actually made it quite difficult for other people to

Figure 4 Cover of the Brooke Bond Tea card album of Prehistoric Animals.

work on the material, [and] by the time he died in the late 1990s, none of it had ever been published — with one exception. [Charig] was also the scientific advisor on [one set of] the Brooke Bond tea picture cards — prehistoric animals. You could collect pictures of various fossil vertebrates and other fossils in packs of tea, and insert them into this picture album[, which was available for the princely sum of five pence in the early 1970s] (Fig. 4). And because [Charig] was the scientific advisor [for the album], he decided to include some of the Tanzanian material within it, [in particular a] reconstruction [and description] of the animal that he had called, in his PhD thesis, *Mandasuchus*. [Thus,] up until earlier this year this [the Brooke Bond album text and picture were] the most detailed scientific description of *Mandasuchus* to ever appear anywhere (Fig. 5). I have actually cited the Brooke Bond picture card album at least three times in scientific publications.

We have been working [on] the *Mandasuchus* material recently, and this year we finally publish[ed] a description of this animal;

Figure 5 Brooke Bond Tea card album page showing and describing Mandasuchus.



9. MANDASUCHUS (*from Manda in Tanzania and Greek 'crocodile'*)
This reptile was a typical pseudosuchian, belonging to the group from which dinosaurs, pterosaurs, crocodiles and birds all evolved. Contrary to what is stated in many books, however, most of the pseudosuchians showed no tendency towards walking or running on their hind legs alone. *Mandasuchus* lived in Tanzania in Middle Triassic times, 210 million years ago. It was of crocodile-like size and build, with large teeth of the carnivorous type, a double row of armour-plates down the middle of the back and hind legs rather longer than the front ones. Its habits too were probably like those of modern crocodiles, though it may have been less fond of the water.

Figure 6 Reconstructive drawing of Mandasuchus *in its ancient environment (© Mark Witton, reproduced with the artist's permission).*

and we had a modern artistic reconstruction, by palaeoartist Mark Witton, of what this animal might have looked like within the Manda Formation (Fig. 6). I am not going to talk in more detail about *Mandasuchus* [for it has] nothing to do with the origin of dinosaurs. [Rather,] it is actually something [to do with the] long lineage leading towards crocodilians.

The animal I really want to focus on is an animal called *Teleocrater*, which [Charig also] worked on [for] his PhD thesis and never got around to publishing. [A] few years back myself and [a] colleague, [Prof.] Sterling Nesbitt, [of] Virginia Tech University, started working on this material again[, including material found in the 1930s by Rex Parrington, another well-known palaeontologist (Fig. 7).

Figure 7 Richard Butler and Sterling Nesbitt working on Teleocrater *material at Natural History Museum, London.*

[Here] is what the *Teleocrater* would have looked like, [in] a skeletal reconstruction that we generated (Fig. 8, *opposite*), based [partly] on our study of the historical material that is in London, but also [on] new material that [Nesbitt] collected as part of [his] new expeditions to Tanzania. The red bones are those present in the collections in the Natural History Museum; *[pointing to colour coding on his slide]* the blue bones are those that [Nesbitt] collected, possibly at the same site, certainly at a site that is very close to the original site; and the purple are bones present in both collections.

[*Teleocrater* was] an animal *c.* 3m in length[, and you] can see that we have a reasonable proportion of the skeleton, which has [enabled] us to get a pretty good idea of what this animal might have looked like. It is depicted here as a quadrupedal animal; walking on all fours, and I would say [it has] an overall Komodo dragon-like appearance.

[The anatomy is] very detailed and probably mainly of interest to a specialist, but I want to highlight a few features in the anatomy [using a skeletal and body plan reconstruction by palaeoartist Scott Hartman] (Fig. 9, *opposite*).

One thing that is distinctive about [*Teleocrater*'s neck] vertebrae is that they are quite elongated: the centrum of the vertebra is quite long. [That is] actually similar to what we see in the earliest dinosaurs, and is [a feature] that, possibly, is the beginning of the neck elongation that we see in classic dinosaurs like *Brontosaurus* and *Diplodocus*.

This is the humerus, the upper arm bone[, its] most distinctive feature is that it has [a] long flange. [At] the head of the humerus, where it would have fitted into the shoulder girdle, [there is] this long flange, which is known as the deltopectoral crest, the site [where] the muscles would have been attach[ed]. [A] long flange indicating powerful musculature attaching to the forelimb [is] one of the things [palaeontologists] have used to identify a dinosaur.

This is the ilium, one of the bones of the pelvis; the bone that connects the pelvis to the backbone, so the sacral vertebrae attach[es] to [the ilium].

This is the acetabulum, where the head of the femur, the thigh bone, fits. Dinosaurs are unusual among reptiles in that they have an open acetabulum — they do not have a wall of bone that closes

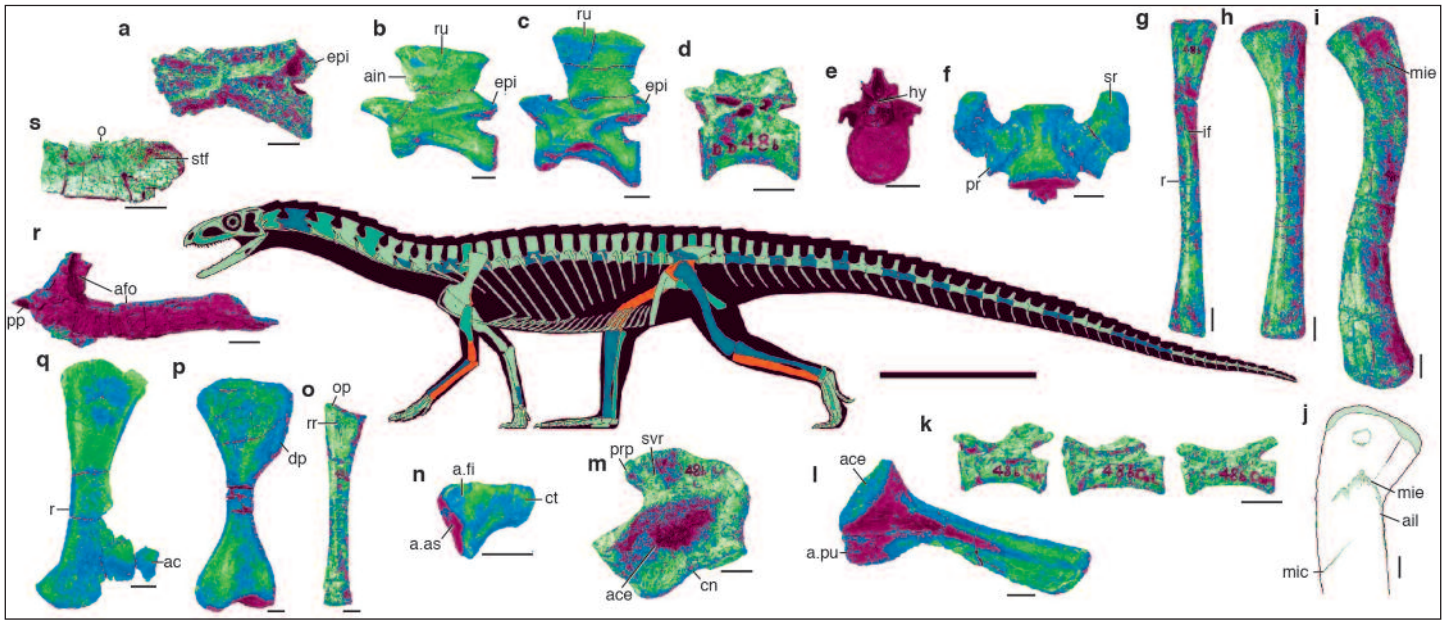


Figure 8 Fossils and reconstruction of Teleocrater (reproduced, with permission, from Nesbitt, Sterling J., Butler, Richard J., Ezcurra, Martín D., Barrett, Paul M., Stocker, Michelle R., Angielczyk, Kenneth D., Smith, Roger M. H., Sidor, Christian A., Niedzwiedzki, Grzegorz, Sennikov, Andrey G., and Charig, Alan J. 2017 'The earliest bird-line archosaurs and the assembly of the dinosaur body plan'. Nature ***544****, 484–7 [27 April 2017]).*

off the acetabulum. [This is another trait] considered a distinctive dinosaur feature. [But although *Teleocrater* has] a closed acetabulum, [it also had a] 'notch' [in it] *[labelled 'NO' on a slide of a an acetabulum]*, which possibly is the beginning of the opening of the acetabulum, the beginnings of a dinosaur-like condition.

This is the femur, the thigh bone[, with a] general sigmoidal shape, quite slender. [However,] if you look at the details, we can recognise [sites] on the head of the femur where muscles would have been attached. The[se sites] are quite subtle, but we can recognise that muscles would have been attach[ed] in various places, and the pattern of musculature present in this animal is similar to what we have been inferring, typically, for the earliest dinosaurs.

[Showing one last picture of a fossil bone] This is a bone called the calcaneum, one of the ankle bones. If you work on dinosaurs and early archosaurs, you get excited about ankle bones, because they have lots of [characteristics that] tell us about evolutionary relationships. This [example], although it does not look like much, has [a] very long tubercle, similar to what [is seen] in crocodiles. Dinosaurs do not have this [feature; instead,] they have a simple ankle, and that is because their limbs just move backwards and forwards with simple roller joints. Crocodiles have much more complex ankles, including large tubercles to which muscles [are] attach[ed]. [Such an ankle bone] is something that we would not expect to see in an animal closely related to dinosaurs; it is a much more primitive feature.

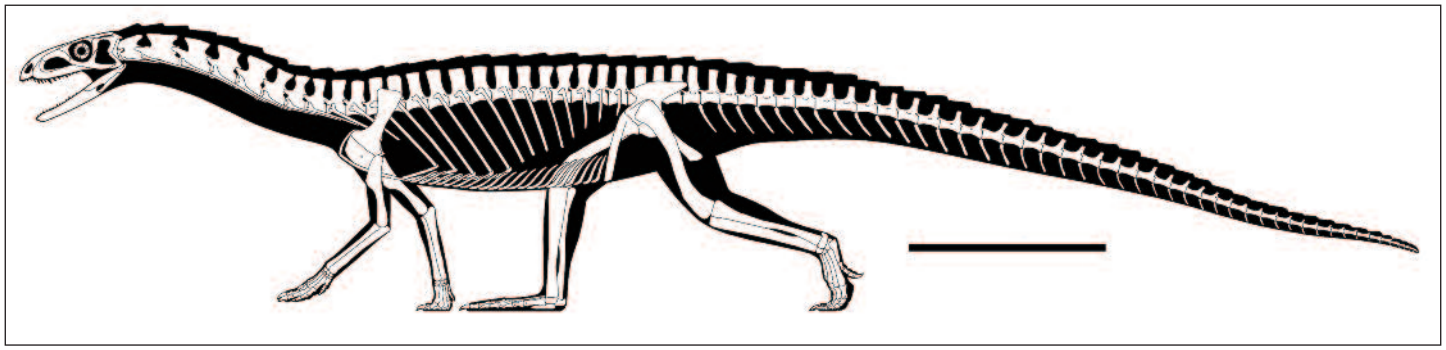


Figure 9 Skeletal reconstruction of Teleocrater *(scale bar = 1m; © Scott Hartman, reproduced with the artist's permission).*

When we code all of this information and crunch the numbers, we build up an evolutionary tree of early archosaurs. I am trying to fit *Teleocrater* into [this group] (Fig. 10, *overleaf*). This is where [*Teleocrater*] falls out, [at] the base of [the] Archosauria, the ruling reptiles *[showing two diverging lineage lines on the slide]*: this is the lineage leading towards crocodiles[, and] this is the lineage leading towards dinosaurs and birds. *Teleocrater* comes out as the earliest member of the [latter] lineage, the Avemetatarsalia. [*Teleocrater* is] right at the base of the avemetatarsalian lineage; [the appearance of *Teleocrater*] potentially tells us something about what the earliest members of the lineage would have looked like, and thus something about where dinosaurs come from.

[showing a slide] [Our] reconstruction of *Teleocrater*, created by palaeoartist Mark Witton, [shows] in some ways [*Teleocrater*] has dinosaur-like anatomy, but in other ways it looks more like a Komodo dragon, with [its] quadrupedal posture, [and] very long, heavy tail. The locomotion, the way it walked, [was] probably more lizard-like in some ways, than a typical dinosaur (Fig. 11, *page 79*).

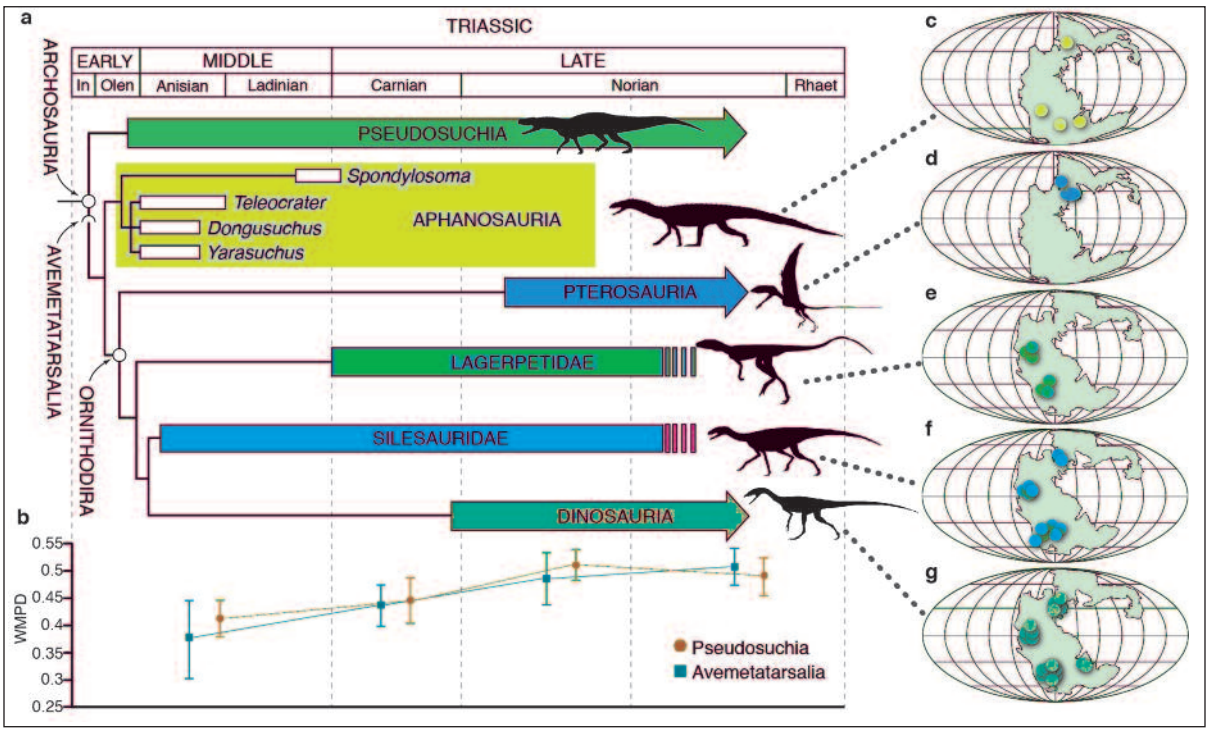


Figure 10 Evolutionary tree of early avemetatarsalians (reproduced, with permission, from Nesbitt, Sterling J., Butler, Richard J., Ezcurra, Martín D., Barrett, Paul M., Stocker, Michelle R., Angielczyk, Kenneth D., Smith, Roger M. H., Sidor, Christian A., Niedzwiedzki, Grzegorz, Sennikov, Andrey G., and Charig, Alan J. 2017 'The earliest bird-line archosaurs and the assembly of the dinosaur body plan'. Nature ***544****, 484–7 [27 April 2017]).*

After we had finished working on *Teleocrater* we started looking through the literature at fossils of the same age from other parts of the world. What we realised was that people have been describing things that looked quite a lot like *Teleocrater*, for quite a long time, but just had not really known what they were. There is an animal from the Middle Triassic in India called *Yarasuchus [showing a slide]*, which was described in 2005. The reconstruction of what *Yarasuchus* might have looked like is almost identical to *Teleocrater* if you look at the individual bones of the skeleton: [for example] the femur. The vertebrae have elongated centra, similar to *Teleocrater*; and the humerus [has the] very long flange that I said was a typical dinosaur feature. We also [found a paper on] an animal called *Dongusuchus [showing another slide]*, from the early Middle Triassic of Russia, named in the late 1980s. Again, the bones of this animal are very similar to those of *Teleocrater*, [with] a femur that is almost identical in shape to that of *Teleocrater*.

So by studying *Teleocrater*, we were able to recognise that there was an entire group of these animals around in the Middle Triassic that people had not realised existed before. [There is another animal from Brazil], described back in the 1940s [when] people did not really know what [these animals] were: they were very enigmatic. So we called this group 'Aphanosauria' — mean[ing] 'hidden reptiles', an allusion to the fact that these animals were hiding, essentially in plain sight. They had been described scientifically, but people did not really know what [their] evolutionary significance was.

What does this mean for understanding dinosaur origins? Traditionally, when we have thought about where dinosaurs come from, what dinosaurs evolved from, we have reconstructed them as looking something like this, an animal called *Marasuchus [showing a slide]* from the late Middle Triassic of Argentina. It is a tiny animal, *c.* 300mm long — it could sit on the palm of your hand, particularly [as] a lot of [it] is tail. It also [has] very elongated hind limbs, so it was a fast-moving, very small animal. It is reconstructed as being insectivorous. *Teleocrater* is different from *Marasuchus*, and from a few other suggestions of what dinosaur ancestors might have looked like. [At *c.* 3m long] *Teleocrater* [was] a much larger animal, [and was] quadrupedal; it [was] probably a much more slowly moving animal. [*Teleocrater* was] probably also one of the apex predators, one of the top predators within its ecosystem, rather than a small, scurrying, insectivorous animal.

So the question now really is, is this our model for what the immediate ancestors of dinosaurs should look like, or is this our model? *[contrasting the reconstructions of Marasuchus to Teleocrater]* [It is to address this question that] a lot of research is going to be happening in the next few years, trying to understand exactly what the ancestors of dinosaurs looked like.

Now I am going to jump forward a bit in time, to the top of the Manda Beds. I mentioned there were two different fossil assemblages within the Manda Beds. *Teleocrater* comes from the old[er] part, but from the young[er] part there is another fossil that might be the oldest known true dinosaur. This is an animal described just a few years ago, called *Nyasasaurus*. Even though he completed a manuscript on it, [Charig] never actually [submitted it for publication]. So this [research] was published a few years back by Sterling Nesbitt and people at the Natural History Museum. One of the reasons that we think [Charig] never published this material is because it is] very fragmentary, so it is difficult to know exactly what it is. [It is from the upper part of the Anisian Stage, dated *c.* 242 to 240 million years ago.]

[We have] an upper arm bone, a humerus, [with a] long flange. [We also have] some of the backbone, parts of the sacrum — the bones that attach the pelvis to the backbone — and a couple of neck vertebrae. The neck vertebrae are quite long [and]

dinosaur-like. [In addition,] there are three vertebrae within the sacrum [one of the classic] dinosaur feature[s], [as] most reptiles only have two vertebrae in the sacrum. If you cut open the bones and look at [their] internal histology, [you can see that the] bone [grew] very fast, [yet] another classic dinosaur feature, as we know that [dinosaurs] grew very fast. [*Nyasasaurus*] is possibly the oldest true dinosaur; but it is difficult to be certain, because [of] its incomplete[ness].

[Although] incomplete, vertebrate palaeontologists, [can still attempt a] reconstruction of the [whole] skeleton *[showing a slide of a reconstructed Nyasasaurus based on its fossil bones]*. [The reconstruction] is informed by a bit more than [just the bones], of course, because we do know that [by our interpretation] it might be a true dinosaur, [and] we know what other early dinosaurs looked like. So this [reconstruction] is largely based on other early dinosaurs, but [is placed in] a Manda Beds [environment].

If we [now] jump forward a bit more in time, to the beginning of the Late Triassic, we have the Ischigualasto Formation, with multiple species of, without a doubt, true dinosaurs present. So what seems to [have] happen[ed] through the Middle Triassic and into the early part of the Late Triassic is a slow spread of dinosaurs and their close relatives across the world. [Here] is a map from the Middle Triassic [Period to] the Carnian [Stage], the beginning of the Late Triassic. Yellow dots [are] where we find] vertebrate fossils, green dots [those of] close dinosaur relatives, and red dots, true dinosaur fossils. [Thus,] we have vertebrate fossils in various parts of the world in the Middle Triassic, but we are only finding close dinosaur [relatives] in the southern hemisphere, in a relatively small area; and that is also where we find the earliest true dinosaurs. So at the moment, we think that dinosaurs and their close relatives originated in the southern hemisphere, somewhere in the Middle Triassic.

[If] we jump forward [still] further in time, to the Norian Stage of the Late Triassic, we start to get to a point where dinosaurs are found worldwide, and are beginning to dominate ecosystems. [Here] is an animal called *Plateosaurus [showing a slide]*. [There have been many discoveries of this animal and of its close relatives in] south-west Germany, parts of Switzerland and France — hundreds, if not thousands, of skeletons of this animal [are] known. [Plateosaurs were] very important in local ecosystems at that [this] time. So by c. 215 million years ago [dinosaurs] dominate[d] ecosystems at least in some parts of the world.

Then, at the end of the Triassic [Period, there was] another mass extinction event. The Triassic/Jurassic boundary is marked by [a massive series of flood volcanic deposits, known as the Central Atlantic Magmatic Province (CAMP) basalts, erupted as North America and Europe began to separate and the Atlantic started to form.] You can see these [basalts] on the eastern coast of the USA and Canada today, also in the Algarve in Portugal, and in Morocco. [The eruptions] seem to have driven climate change, leading to [the mass] extinction event.

[In] a typical Late Triassic scene [a reconstruction of the south-west USA] *[showing a slide]*, the dinosaurs are only [shown] in the background. Other groups of archosaurs —phytosaurs, aetosaurs [and] rauisuchians — all [went] extinct at the end of the Triassic, and only the dinosaurs and the flying reptiles (pterosaurs) [survived] — and take over global ecosystems everywhere in the earliest part of the Jurassic [Period].

The take-home message is that it [took] a long time for dinosaurs to get from originally evolving to the point [at] which

Figure 11 Life reconstruction of Teleocrater *in its Manda Beds environment (© Mark Witton, reproduced with the artist's permission).*

they [dominated] global ecosystems. We have the oldest true dinosaur, possibly, in the Anisian Stage [of] the Middle Triassic, [and] their close relatives somewhat earlier in the Anisian; but it is not until the Jurassic, some 45 million years later, that dinosaurs completely dominate terrestrial ecosystems — a long, slow rise to dominance.

I think the other key message [of] recent [research on] dinosaur evolution is that it is a story of two mass extinction events: [one] at the end of the Permian [that] wiped out lots of other vertebrate groups, and [one at the end of the Triassic that wiped out] lots of groups that [were] potentially competing with dinosaurs. [In] the aftermath of [the Permian] extinction archosaurs, including dinosaurs, [were] able to diversify. And then at the end of the Triassic dinosaurs [were] able to expand into [the] vacant ecological space [that it created]. So maybe without these two mass extinctions we would not have had dinosaurs, or they would not have been as successful as they were.

I said I would mention local geology a bit at the end [of my talk]. There are lots of rocks here in the UK of similar age to those in Tanzania, where [palaeontologists have] been collecting, [including finding] animals like *Teleocrater*, e.g. in] the Otter Sandstone [now reclassified into the Helsby Sandstone Formation, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=OS] just west of Sidmouth in Devon. Much of the Midlands [are] also underlain by Triassic rocks of similar age. These [areas] have not been quarried extensively, but historically they have yielded quite a lot of vertebrate fossils. You can still find vertebrate fossils today in the Otter Sandstone. Historically, the rocks here in the Midlands have yielded animals called rhynchosaurs most commonly *[showing a slide of a rhynchosaur skull, pointing out its eye socket, upper jaw and hook-shaped beak]*. This is not a dinosaur; [it is] distantly related to dinosaurs, [and] common in the Middle Triassic, a kind of pig-like herbivorous animal. [Many more rhynchosaur fossils have also been found] in Shropshire, Warwickshire and Worcestershire as well.

[Here] is a reconstruction of what the Midlands might have looked like at the time the first dinosaurs were appearing and diversifying. This is a recent reconstruction done for the Warwick Museum by Bob Nicholls, a palaeoartist, based on material in the Warwick Museum's collections. [Notice the presence of] rhynchosaurs. There are [also] some crocodile-like amphibians in the background; [and] a predatory animal called a 'rauisuchian' skulking in the background. But what we do not have in this picture are dinosaurs, or close dinosaur relatives. It may be that they were not present in this part of the world during the Triassic; but it may be that we just have not discovered them yet. I think our best opportunity to discover [any] in the future will be in the Otter Sandstone [now reclassified into the Helsby Sandstone Formation, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=OS]. [Perhaps] at some point in the future we will have some dinosaurs or some close dinosaur relatives to fit into this scene, as well.

[Prof. Butler finished his lecture by showing a few slides to promote the Lapworth Museum of Geology at the University of Birmingham. After £2.5 million redevelopment and its re-opening, new displays were opened in the temporary exhibition space, created by Prof. Butler and a colleague from the English Literature Department, on changing scientific and artistic depictions of dinosaurs over the last 200 years. The display finished in October 2018.]

The importance of water in aeolian systems; an example from the Sherwood Sandstone of the West Midlands

Oliver Wakefield

British Geological Survey

Introduction

The preserved sedimentary expression within dry-land environments was traditionally thought to be the product of either extensive ephemeral (short-lived) fluvial sedimentation or dominated by windblown migrating dune-forms. However, within the last few decades increasing evidence has shown that few dry-land environments remain solely the remit of either aeolian or fluvial processes, but are commonly a mix of both. A number of interactions between these depositional media are increasingly being identified within dry-land environments and these have been shown to occur on a variety of scales, as either symbiotic or competitive in nature.

Examples of the interactions between fluvial and aeolian facies are observed within the Triassic aged Sherwood Sandstone Group, of western and central parts of England (in and around the Cheshire Basin). On a national scale the Sherwood Sandstone is primarily of fluvial affinity, with its source situated in modern-day north France. The fluvial system of the Sherwood Sandstone Group flowed in a northerly direction across southern and central England from northern France, covering large portions of the Triassic land surface in eastern and western England (the Midlands) and infilling numerous different basins (Fig. 1). Where the fluvial system entered the Cheshire Basin in western England it interacted with a contemporaneous aeolian dune-field, leading to a number of different styles of system interaction.

Rationale

An improved understanding of the range of aeolian-fluvial interactions within dry-land systems and how these processes impact the resultant sedimentary architecture has applied considerations. Firstly, it enables the development of predictive models with which better to account for the palaeoenvironmental significance of the geological record. Secondly, it is important for the development of models that predict sandbody connectivity and heterogeneity, concepts important in the search for, and development of, economic reserves of oil, gas, minerals, water, and carbon capture and storage. This is important in the context of the Sherwood Sandstone Group due to a number of applied fluid flow considerations:

- The Sherwood Sandstone is designated as a principal aquifer in the UK, providing the main source of groundwater for significant parts of the Midlands and northern England (Allen *et al.* 1997; Wakefield *et al.* 2015);
- The group is a hydrocarbon (gas) reservoir in the offshore East Irish Sea Basin (Meadows and Beach 1993a);
- Lateral equivalents of the Sherwood Sandstone in the North Sea are productive (Gray 2014);
- Its spatial setting in the subsurface, often juxtaposed with Carboniferous Coal Measures strata, and also forming rockhead under major conurbations, has resulted in a contamination legacy associated with past industrial use (Bouch *et al.* 2006; Hough *et al.* 2003);

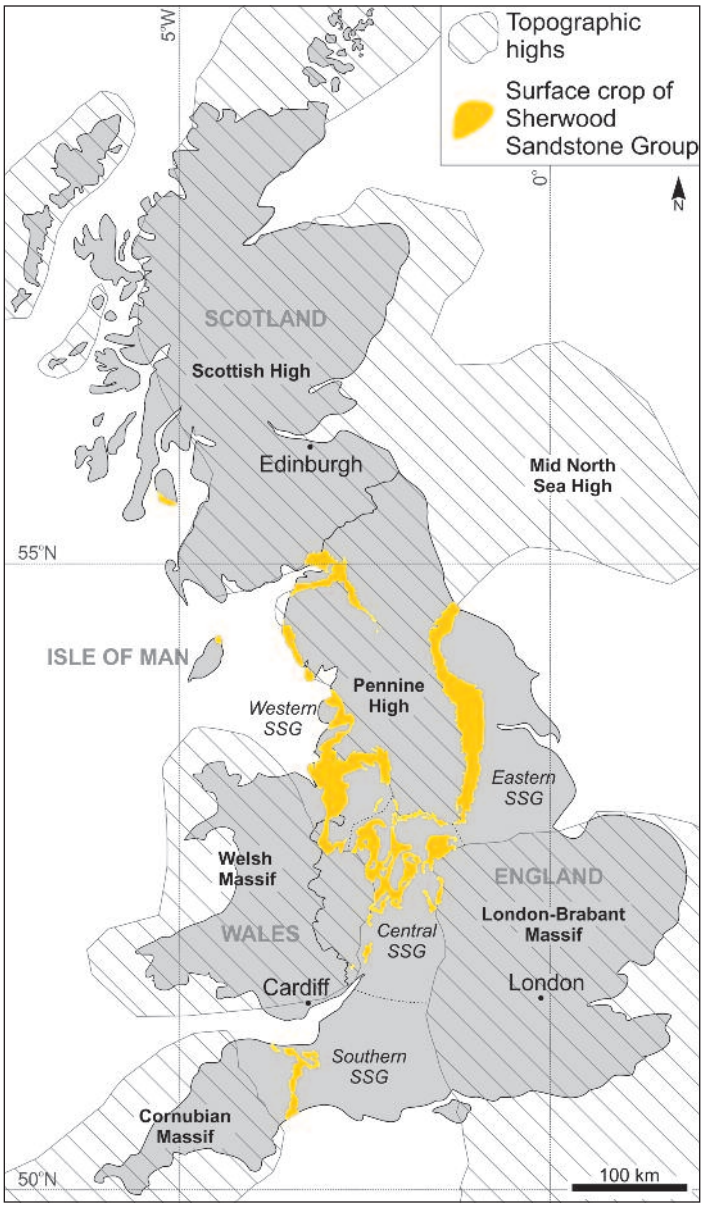


Figure 1 Map of Sherwood Sandstone Group: infilled basins in southern and central England, covering large portions of the Triassic land surface in eastern and western England (the Midlands).

- The pore-space within the Sherwood Sandstone is a potential economic resource, both in terms of extraction of pore-fluids (groundwater and hydrocarbons), and the re-use of pore-space as a potential CO_2 store, as a source of shallow geothermal energy, and as a host for compressed air energy storage (Evans *et al.* 2009; Evans and Chadwick 2009).

1 Aeolian bedforms

The ability of fluvial waters to penetrate aeolian dune-fields (like the example of the Sherwood Sandstone in the Cheshire Basin) is governed primarily by the arrangement and geometries of present sand dunes (dune-forms). The presence of aeolian

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dune-forms, by virtue of their relief, act as barriers and guides to flowing water in the dune-field. This is despite the fact that it has long been recorded that some more extreme incursive water events can have sufficient vigour and duration to cut through and remove some dune-forms (Bullard and McTainsh 2003; Langford 1989; Mountney 2006b). Within modern dry-land systems this dune dissection or 'dune breaching' interaction is more often associated with repeated gradual erosion of dune-forms over a period of time by separate discrete flood events (Fig. 2). The timing of such flood events would have to be sufficiently spatially constrained to prevent the aeolian system from rebuilding and 'healing' the damaged dune-forms. Despite examples of sand dune breaching from modern and ancient systems, the ability of water to occupy parts of the aeolian system is still primarily governed by the aeolian dunes. As such, factors controlling the orientation, size, shape, wavelength and migration speeds of aeolian bed-forms, and thus the low-lying inter-dunes, are all important in understanding the resultant and potential interactions that can occur. The following section provides an overview of the some of the interaction types identified within the Sherwood Sandstone Group.

2 Inter-dune flooding

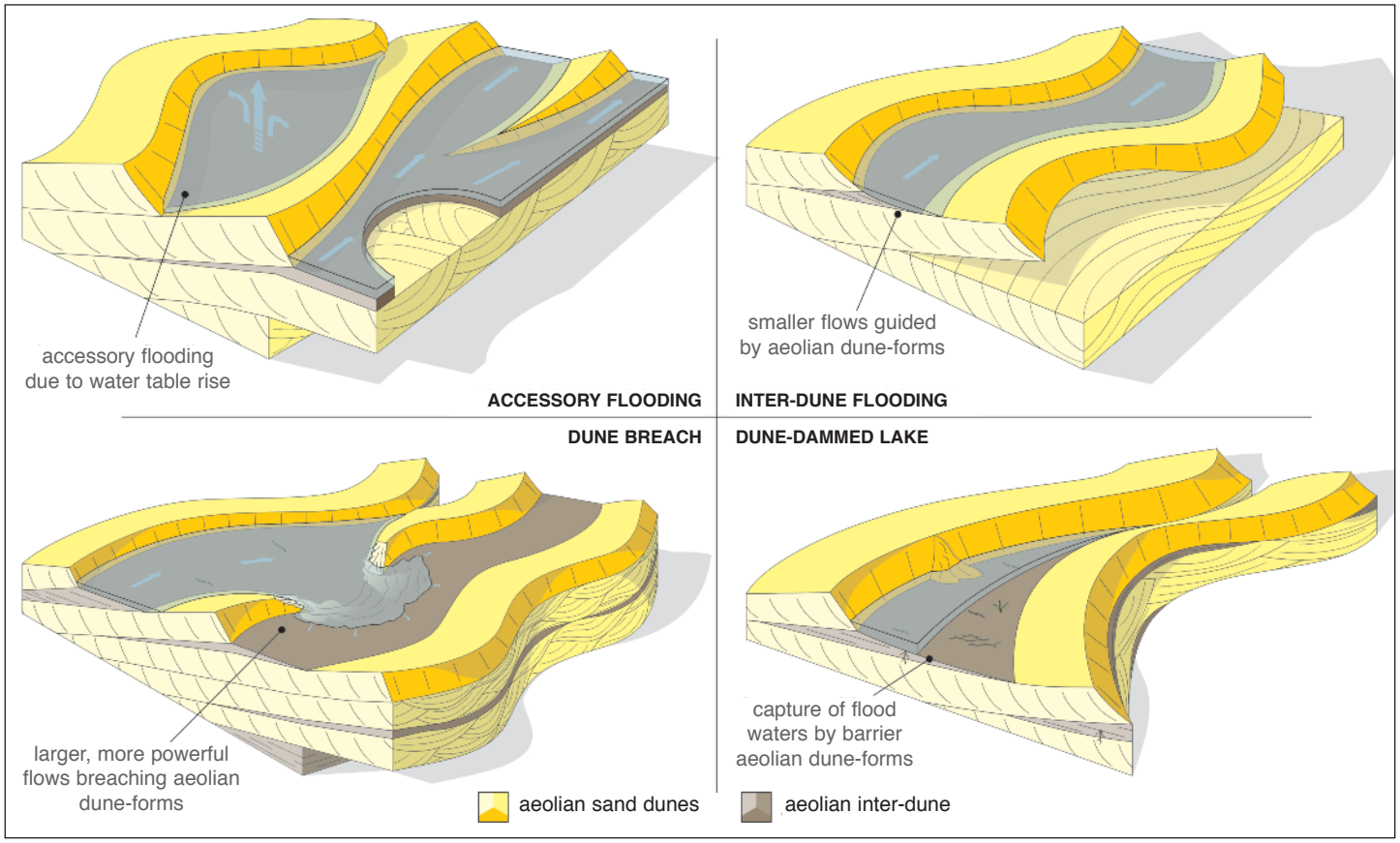
Description

These are thin, red-brown, homogenous, structureless, fine- to medium-grained sandstones (up to 1m, commonly <0.6m). They are confined by highly homogenous, white-yellow, cross-bedded sandstones. In sections parallel to palaeowind direction, the elements exhibit a broadly horizontal tabular geometry that extends for hundreds of metres where outcrop allows. The lower bounding surface of these elements is sharp, irregular and commonly slightly erosively based. The upper bounding surface is also sharp, forming as broad near-horizontal straight surfaces with some minor local-scale irregularity. The upper boundary also sometimes exhibits a stacked onlap relationship (feathered) with the above cross-bedded sandstone unit. In sections perpendicular to palaeowind direction these elements have a broadly lensoidal shape, where they have lateral extents of tens of metres, though they often occupy the same stratigraphic horizon as other such lenses. Internally these elements frequently comprise massive red-brown sandstones, with some examples containing small pebble-sized clasts of smeared mudstone. Sometimes rare thin lenses of white-yellow sandstone, only a few grains thick, are observed. These white-yellow lenses can extend up to 200mm laterally and are orientated as horizontal to near-horizontal planes.

Interpretation

This element is interpreted as representing an open inter-dune corridor along which water flowed episodically (Kocurek 1981; Lancaster and Teller 1988; Mountney and Thompson 2002). Smeared mud clasts represent rip-up clasts of a more local origin. The structureless nature of the element, the sharp erosive lower boundary and sharp upper boundary suggest rapid deposition with relatively abrupt cessation. The presence of small mudstone pebbles suggests a sub-aqueous, rather than subaerial, depositional medium. The absence of observed indicators of 'drying' suggests rapid water loss from a 'short-lived event', which prevented the generation of such structures. Indeed the sharp upper bounding surface to this element also suggests abrupt cessation of deposition, supporting the notation of a rapid loss of water (Ahlbrandt and Fryberger 1981).

Figure 2 Dry-land system dune dissections or 'dune breaching' showing interaction associated with repeated gradual erosion of dune-forms over time by separate discrete flood events.


accessory flooding due to water table rise
ACCESSORY FLOODING
smaller flows guided by aeolian dune-forms
INTER-DUNE FLOODING
DUNE BREACH
larger, more powerful flows breaching aeolian dune-forms
DUNE-DAMMED LAKE
capture of flood waters by barrier aeolian dune-forms
aeolian sand dunes
aeolian inter-dune

Observed instance of a feathered upper bounding surface indicates coeval flooding of the inter-dune with aeolian dune migration. The inclusion of millimetre-scale white-yellow lenses is interpreted as minor reworking of the underlying sand dune facies during flooding.

3 Inter-dune lakes: dune damming

Description

These comprise up to 1.5m thick lenses that can have lateral extents, both parallel and perpendicular to palaeowind direction of tens of metres. These lenses are situated within and compartmentalised by white-yellow cross-bedded sandstones. Lower and upper bounding surfaces are sharp with upper bounding commonly exhibiting polygonal cracks that are frequently infilled by overlying white-yellow sandstone. Internally, this element comprises numerous facies types, including laminated sandstone, laminated siltstone and mudstone, and rippled sandstone. Ripple-forms within this element are symmetric and have crest heights up to 20mm with observed wavelengths from 50mm to 150mm. Crestline orientations are variable, but have a modal orientation perpendicular with palaeowind directions.

Interpretation

This element represents a dune-dammed lake or pond (Fig. 2). Observed examples of symmetric ripples are indicative of wind-agitation on standing bodies of water. The presence of polygonal cracks (desiccation cracks) indicates episodic drying of standing water. Examples of the desiccation cracks at the lateral margins of this element result from the lake or pond margins being most sensitive to changes in the water level. The presence of ponded water is likely the result of a dune-form configuration that was at least partially enclosing the inter-dune, preventing water escape by further flows.

4 Accessory flooding: water table rise

Description

Thin lensoidal shaped elements with lateral extents up to 10m in palaeowind parallel and perpendicular sections. The lower bounding surface of these lenses is often diffuse and relatively hard to define, as it is compositionally indistinct from the underlying facies types from which it is clearly reworked. As such, the disruption or absence of the original sedimentary structure (cross-bedding) commonly defines the base of this element. The upper bounding surface is frequently undulose or feathered with the overlying white-yellow cross-bedded sandstones. Internally this element contains white-yellow sandstones that exhibit wind-ripples, horizontal amination, deformation (contortion) and asymmetrical ripples. Vertical calcrete nodules are also sometimes observed in the upper portions of the element.

Interpretation

This element is interpreted as accessory flooded, wet inter-dunes that was fully enclosed by aeolian sand dunes (Fig. 2). The presence of water is indicated by: rare examples of asymmetric ripple-forms, interpreted as wind-agitated subaqueous ripples; deformation structures associated with dewatering, likely resulting from compression by the overlying migrating sand (Mountney 2006a); and plant colonisation evidenced by small rooting (vertical calcrete nodules).

Unlike dune dammed inter-dune ponds and lakes, this element has a complete absence of any fluvial facies types and instead comprises facies from aeolian origin or reworked aeolian facies only. This absence of fluvial facies suggests that the inter-dune form was isolated from the fluvial system. The water present within the dune-field could have been sourced either by a water table rise above the level of the inter-dune surface, or as infilling by rainfall within the system. A water table rise is the preferred interpretation, as the volume of water and duration of rainfall needed to sustain a standing body of water for a significant period of time (to enable plant colonisation or the formation of wind-agitated ripples) likely precludes rainfall as the mechanism.

The interpretation of the inter-dune being completely enclosed necessitates that the surrounding (bounding) sand dunes had sinuous crestlines. It also suggests that the bounding sand dunes to the inter-dune were likely relatively closely spaced (short-wave lengths) and were most probably arranged in an out-of-phase configuration.

Conclusion

Deposition of aeolian and fluvial systems in dry-land environments can lead to a number of different interaction types. Study on the mixed aeolian-fluvial Sherwood Sandstone Group of the Cheshire Basin, reveals three distinct types of interaction:

(i) inter-dune flooding,
(ii) dune damming, and
(iii) accessory flooding.

These interactions form as a result of aeolian sedimentation (sand dunes and inter-dunes) occurring coevally with sources of water from fluvial systems, water table rises or rainfall. An understanding of these interactions is important as they can add local- to regional-scale heterogeneity, which might be impactful on fluid flow with the preserved sedimentary deposits.

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Summary of the 46th OUGS Symposium 'Music of the Earth'

Dr Susanne Schwenzer, OUGS President

(Senior Lecturer in Earth Sciences, The Open University)

As a new OUGS President, allow me to start with a few words of introduction: I am a Lecturer in Earth Sciences at the School of Earth, Environment and Ecosystem Sciences at the Open University. I teach Earth Sciences and I am a mineralogist by my own undergraduate training. For my PhD I diverted to a planet that has lots of deserts, which is Mars. I first studied noble gases in Martian meteorites and I am now part of the NASA Mars Science Laboratory 'Curiosity' rover science team, and a few times a month also on the operations team helping to decide where the rover drives. For my research I am looking at alteration minerals and how they form in the Martian environment. All of this also reflects in my teaching — for example, we have a Masters module where we run a mission simulation that was completely designed by the OU.

Most importantly, the Symposium was a great success, with many very interesting talks. My thanks go to the Organisation team Don Cameron, Ian Clarke, Sandra Morgan, Norman Nimmo-Smith and Janet Hiscott, who have put together a very interesting programme inside and outside the lecture hall! We greatly appreciate all field trip guides and the leader of the petrology workshop, who put together a very interesting and diverse set of activities for the Saturday afternoon. But there is more to making a day like this happen. Many thanks to those who have spent countless hours working on every little detail to make those two days a great success. Another big thank-you also goes to all the volunteers who, beyond this Symposium, make the OUGS, who the OUGS is: an active organisation with many interesting events, with newsletters and get-togethers. Thanks to all, who help all through the year, and in the 17 local branches.

The topic of the 46th Annual Symposium, held in Worcester, was 'Music of the Earth', the title playing on the birthplace of the great English composer, Sir Edward Elgar and combining it with the silhouette of the Malvern Hills. The Symposium encompassed two days of interesting rocks — from very dry to very wet, and from building stones to the places that they came from. The first introduction to the topic was given by Prof. Ian Fairchild, who equipped us with all the background of the Worchester–Malvern area we required for the days ahead, but also with the materials to study the region in greater detail and come back one day to expand on what we learned during the Symposium. Most importantly, he pointed out that this information is available through Apps and on the Internet for everyone to access.

'A brief history of geological time in the building stones of Herefordshire and Worcestershire' by Kate Andrew showed how the building stones and their availability actually influence what has been built. One of her statements made me think, because it is so logical, but I had never considered it that way before: When you see a wall, the quarry is right there. Stone comes at high cost of transportation, as it is very heavy. Investing a lot of effort into transport of materials makes sense for houses and other buildings, of course, but for something as simple as a divider between properties the cost of transport very quickly outweighs the benefits. Kate introduced us to a project that researches into all the building stones in the area, how buildings were erected using the different materials, and the effects of this on preservation and conservation of the historic heritage.

Martley Rock became famous due to its first mention in the printed literature by Sir Roderick Impey Murchison in his book, *The Silurian System*, published in 1839. His visit in 1839 made the site famous and it became a 'must see' site to many naturalists and geologists. Unfortunately, in the 1980s the site was filled in. Susan Hay and William Barclay summarised the history of the famous–forgotten–famous-again site, and the different research strands that were carried out in the area. A project called the 'Martley Rock Project' received EU 'Leader' funding twice, which funded the excavation of two sets of trenches to understand the petrology and stratigraphy of the site. In a nutshell, the rocks span from the Precambrian to the Triassic and are brought together by a set of very complex tectonic movements along the Malvern Fault. More on the tectonic history was also presented by Don Cameron on behalf of Dr Tim Pharaoh. Exceptionally well explained by the experts, I can only direct the interested readers to the summaries of the talks themselves. *[Editor's note: Dr Pharaoh has written a full article on the 'The complex tectonic evolution of the Malvern region', the topic he intended to present in his lecture.]*

The Teme Valley Geologic Society is part of the local team that brings the geology of the region back to life — and most importantly makes it accessible to interested locals and travellers. David Cropp told the story of the society — how the enthusiasm of a few spread across an entire village. Getting them to buy in to volunteer-led projects is not easy, but David showed us how it can be done, and can be done in a sustainable, positive and supportive way that integrates the needs of many different local players. Local volunteers, many of whom have the heritage on their own properties, have become custodians and stewards of that heritage, because they fell in love with what is there, and want to preserve it for generations to come.

Prof. Ian Fairchild presented the talk of Prof. John Mather, who focused on the Malvern water from two perspectives: the hydrology and the merchandise. Hydrologically, because the wells are of course connected to the geology and fault system. What makes this water famous is how it was advertised at a time when drinking water cures were in fashion. I am personally familiar from my own studies with some natural waters used for spa and drinking purposes. One of the rather famous ones occurs in the city of Wiesbaden (Germany), where it is accessible in wells of varying temperature from 70°C to about 30°C. The water in Wiesbaden has a distinctive smell and taste due to its high content in various salts, including sulphur species. We learned during the Symposium that the Malvern water had none of those features, and consequently it was advertised as the most-pure water — bottled and sold for having 'nothing' in it! The wells were exploited commercially on the grounds of delivering very pure water for a long time. Prof. Fairchild covered a second topic related to the ascending water: tufa. With impressive images he showed how a landscape forms from all its geologic elements — Precambrian to present — but he also pointed out that the tufa is a very lightweight building stone that can be used for arches and

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the highest parts of stone structures, wherever a lightweight material is required.

Isotopes — scary for some, but certainly not for an OUGS audience — were the tool of the next study: Dr David Ray used carbon isotope and sequence stratigraphy to study the record of the Wenlock Series (Silurian) of Worcestershire and the surrounding Midland Platform. We learned how the bentonites enable the precise dating as a support of the stratigraphy and to correlate over very long distances, because such ash layers cover large areas of the land surface. Those correlations work from outcrop to outcrop in the local area, but then also over a 1,500km distance.

Following the isotopes was a self-proclaimed 'gallop through the geologic history of Wales and the Borderland' by Dr Nigel Woodcock — and it certainly was a fast-paced tour! Nigel covered all eons, and the history of all the geology, from rifting, to volcanoes, and to sediments … As someone who was exposed to the topic for the very first time, I found it fascinating and very informative, but once again refer to the original article for a summary!

Focusing on a much smaller period of time, Prof. Richard Butler brought a very intriguing part of palaeontology to us in 'The Triassic rise of dinosaurs'. In contrast to most talks I have ever heard, this was not about the (in)famous *Tyrannosaurus rex,* which — as we all 'know' — roamed the 'Jurassic world' but was actually Cretaceous! Instead, this talk showed the beginnings of the development of a species long before the 'T-Rex' that every young child knows and adores. Richard brought together the history of research on the very important pieces of evidence, from a first discovery and description of the creature — *Teleocrater* — the analysis of which has enabled us to place it in the tree of life, and to reveal the importance of the species itself.

Last but not least was a topic that could as well have been Martian: Dr Oliver Wakefield showed the role of water in aeolian systems. Of course, his examples came from Earth, more precisely, from the region called the Sherwood Sandstone of the West Midlands. Oliver compared the dunes of the Sherwood Sandstone with the big active dune fields of today's Africa and examples of sandstones in Utah. There, sporadic flood events cause cementation of the dunes and with that change the entire dynamics of the landscape.

Overall 'Music of the Earth' was a well-composed piece, with fast paced *prestissimo* and allegretto passages moving via *lentando* to *adagio* and *accelerando* back to *allegretto*!

The *coda*: a well-earned 'Thank you!' to all.

OUGS Members Articles

Lamprophyres: a short introduction

Duncan Woodcock

Introduction

A lamprophyre is a distinctive type of porphyritic dyke rock that is often easily recognised in the field (Rock 1977). Lamprophyre means 'glistening porphyry' (Greek: *lampros*, glistening), and refers to the appearance of a hand specimen when light is reflected off the mica phenocrysts that are abundant in some lamprophyres (Fig. 1).

Lamprophyres have a set of characteristics that make them sufficiently distinctive to be considered as a separate group of igneous rocks (Rock 1987; Le Maitre 1989):

(i) they are generally porphyritic, with mafic phenocrysts only that are dominated by biotite-phlogopite or amphibole (both hydrous minerals),
(ii) felsic minerals are present in the groundmass only,
(iii) they usually occur as dykes,
(iv) they are often altered (Fig. 2), particularly the groundmass, although phenocryst phases may sometimes also be selectively altered.

Traditionally, there was a tendency to regard lamprophyres as petrological curiosities with obscure origins. More recently, lamprophyres have been recognised as petrologically significant (Rock and Hunter 1987), particularly as there appears to be an association of lamprophyre dykes with certain classes of gold deposits (Rock and Groves 1988; Chen *et al.* 2014). In this article I aim to provide an introduction to these fascinating and, at times, frustrating rocks.

Classification

Lamprophyre classification is based on the distinctive mineralogies of the different types. Rock (1977) distinguishes three groups of lamprophyres.

(i) Calc-alkaline lamprophyres, with biotite and/or hornblende phenocrysts, and with feldspar as the principal felsic mineral in the groundmass. Calc-alkaline lamprophyres are usually associated with granitoid plutons in orogenic belts.
(ii) Alkaline lamprophyres, with phenocrysts of biotite, dark brown amphibole (usually kaersutite) or olivine in a groundmass containing both feldspar and feldspathoid. Alkaline lamprophyres are usually associated with alkaline igneous complexes on cratons or in rift valleys.
(iii) Ultramafic lamprophyres, with phenocrysts of phlogopite and/or olivine in a groundmass that contains perovskite, carbonate and melilite. The presence of melilite gave rise to the alternative name of melilitic lamprophyres for this group. Ultramafic lamprophyres are associated with alkaline ultramafic-carbonatite complexes in continental rift valleys; they are much less common than the other groups of lamprophyres and I do not consider them further here.

Figure 1 A hand specimen (60mm long) of a mica lamprophyre from a dyke in Skirwith Quarry, Ingleton, N. Yorkshire. Acadian deformation of the dyke has imparted a slight foliation to the rock, which accentuates the 'glistening'.

Table 1 shows the classification of calc-alkaline lamprophyres. This classification had been in general use for some time (Nockolds *et al.* 1978) and was adopted by the International Union of Geological Sciences (IUGS) Subcommission on the systematics of igneous rocks, which deliberated in the 1980s. The classification has two 'dimensions': the predominant mafic

Figure 2 Part of a hand specimen of a mica lamprophyre from St Abbs Head, Berwickshire. This specimen is much more altered than the lamprophyre in Figure 1; however, mica phenocrysts are still clearly visible (field of view = 30mm × 20mm).

Table 1 Classification of calc-alkaline lamprophyres

Calc-alkaline lamprophyres		Predominant mafic mineral	
		Mica (usually biotite)	Hornblende
Predominant feldspar	Alkali (orthoclase)	**Minette**	**Vogesite**
	Plagioclase	**Kersantite**	**Spessartite**

References: Nockolds *et al.* (1978); Le Maitre (1989)

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Table 2 Classification of alkaline lamprophyres

Alkaline lamprophyres		Predominant felsic mineral	
		Feldspar	Feldspathoid
Predominant feldspar	Alkali (orthoclase)	**Sannaite**	**Monchiquite**
	Plagioclase	**Camptonite**	

References: Rock (1983b); Le Maitre (1989)

mineral and the predominant feldspar in the groundmass. In cases where the groundmass feldspars are altered beyond recognition in thin section the terms 'mica lamprophyre' and 'hornblende lamprophyre' are appropriate descriptors.

Table 2 shows the currently accepted classification of alkaline lamprophyres, as developed by IUGS (Le Maitre 1989). The classification is based on the nature of the felsic minerals — as these may be altered, classification may be difficult.

Petrography

Table 3 summarises the mineralogy of calc-alkaline lamprophyres and alkaline lamprophyres. The study of lamprophyres can be frustrating as they have a tendency to alteration — in some cases beyond recognition.

The hand specimens shown in Figures 1, 3, 4 and 5 *(opposite)* are from localities where alteration is minimal. Figures 6, 7 and 8 *(opposite)* show thin section views of a selection of lamprophyres.

Figure 3 A hand specimen (50mm long) of camptonite, an alkaline lamprophyre, from Hoxa foreshore, South Ronaldsay, Orkney. Camptonite dykes are common in Orkney; however, at this locality the dykes are minimally altered and contain unusually large phenocrysts of amphibole. Figure 6 shows a thin section view of a sample from the same locality, but with smaller phenocrysts.

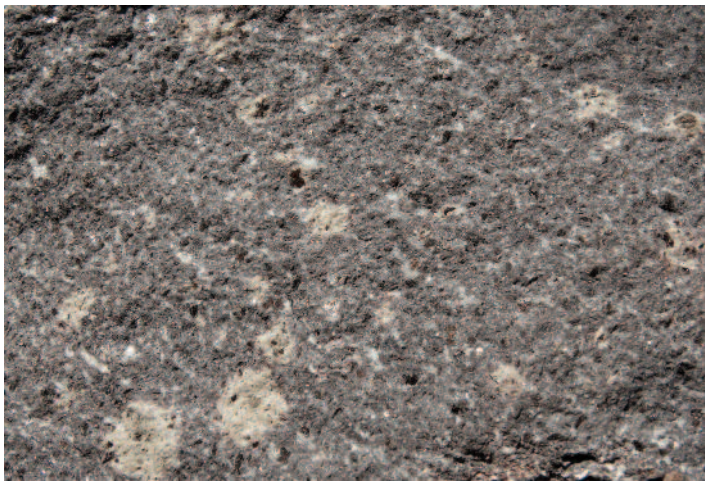


Figure 4 Part of a hand specimen of minette, a calc-alkaline mica lamprophyre, from Killerton Park quarry, Devon. Unlike many of the minettes in SW England, the minette at this location is relatively unaltered. It comprises small but conspicuous mica phenocrysts in a grey groundmass that contains several more felsic patches called ocelli (field of view = 60mm × 40mm).

Table 3 Lamprophyre mineralogy

		Calc-alkaline lamprophyres	**Alkaline lamprophyres**	**Alteration products**
Mafic minerals • phenocrysts and in groundmass	Mica	Biotite: strongly pleochroic, light/dark brown Phlogopite: brown rims, paler core	Biotite: strongly pleochroic, light/dark brown	Chlorite
	Amphibole	Hornblende: pleochroic, green or brown	Alkali amphibole: pleochroic, dark brown (kaersutite)	
	Pyroxene	Diopsidic augite: colourless to pale green with minor zoning	Ti-augite: often zoned with purple rim	
	Olivine	Uncommon and usually altered	Common and often altered	Serpentine, chlorite, carbonate, magnetite
Felsic minerals • in groundmass only	Plagioclase Orthoclase	Present, but often altered		Sericite, epidote, carbonate
	Feldspathoid	Absent	Analcite	
Accessory minerals • in groundmass only	Quartz	Common	Absent	
	Apatite	Common, usually acicular		
	Opaques			

References: Nockolds et al. (1978); Rock (1983b, 1987)

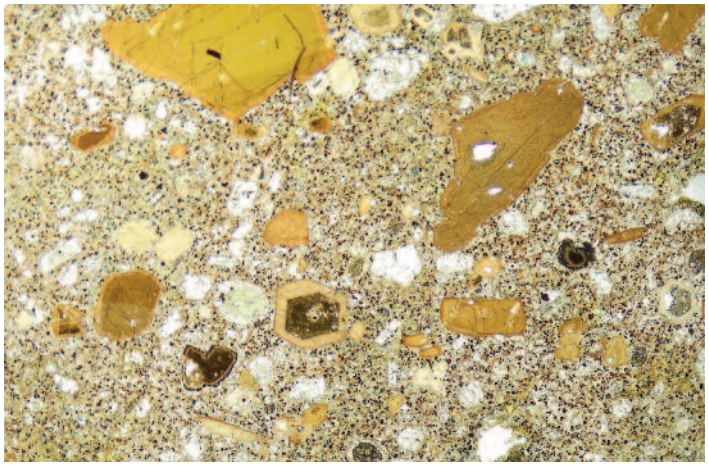
Figure 5 A hand specimen (50mm long) of vogesite, a calc-alkaline hornblende lamprophyre, from Skiag Bridge, Assynt. The hornblende crystals in this specimen are small and elongate, and thus inconspicuous. The groundmass appears slightly pink, suggesting that alkali feldspar is abundant. Figure 8 shows a thin section view of the hand specimen.

Occurrence and UK examples

Calc-alkaline lamprophyres tend to be associated with post-orogenic granitoids. Late Caledonian mica lamprophyres (mainly kersantites) are widely distributed in northern England and southern Scotland, where they occur as dykes intruding lower Palaeozoic sediments (principally Ordovician and Silurian greywackes). Many of these dykes have radiometric ages of 420–400Ma and their intrusion occurs within the period of Acadian deformation (Stone *et al.* 2010); in consequence these lamprophyres sometimes show a preferred alignment of their mica phenocrysts (Fig. 1). Early Permian minettes occur in south-west England, where they were emplaced along with the Cornubian batholith at the end of the Variscan orogeny (Leat *et al.* 1987).

Alkaline lamprophyres tend to be associated with regional extension. The distribution of Permo-Carboniferous alkaline lamprophyres in the Scottish Highlands and Islands was reviewed by Rock (1983a). Particularly accessible examples occur in Orkney (Fig. 9, *overleaf*), where a high proportion of the igneous rocks are lamprophyres (Flett 1900).

Figure 6 Thin section view of the camptonite specimen from Hoxa foreshore, South Ronaldsay Orkney. This plane polarised light (PPL) view shows phenocrysts of a brown pleochroic amphibole (probably kaersutite) with occasional phenocrysts of a pale green pleochroic augite (field of view = 10mm × 7mm).



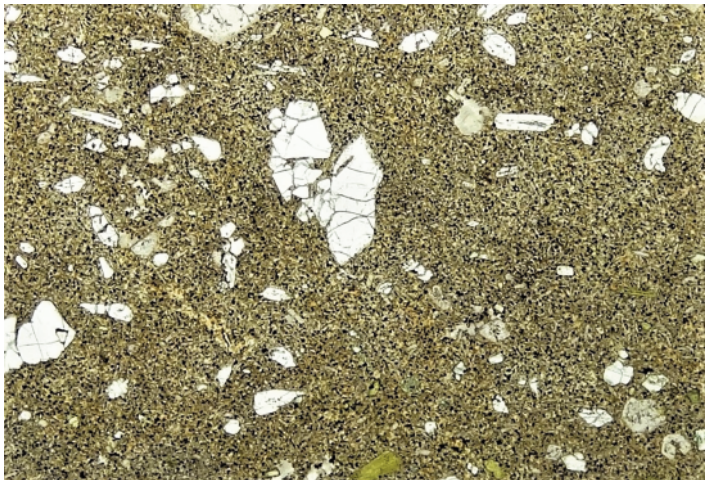


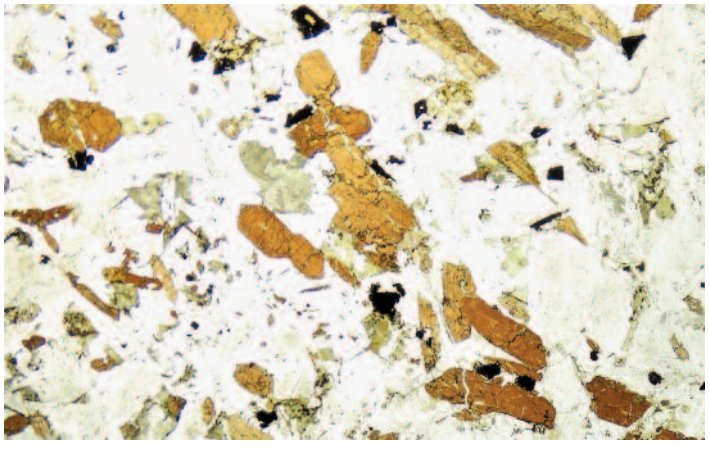
Figure 7 Thin section PPL view of a monchiquite showing euhedral olivine phenocrysts in a fine-grained groundmass. This rock crops out as a series of dykes on the foreshore at St Monans, Fife; (field of view = 5mm × 4mm).

Petrogenesis

In his recent textbook on igneous rocks, Gill (2010) comments that "… lamprophyres — though among the most widespread of alkali rocks — are also the least understood in petrogenetic terms". Some progress has been made recently in understanding the origins of lamprophyres. I consider two aspects: the likely nature and origin of lamprophyre source rocks together with mechanisms for partial melting of this protolith.

The geochemistry of lamprophyres is characterised by enrichment in large ion lithophiles (LILs) such as K, Rb, Ba and Sr and in light rare earth elements (LREEs) together with depletion in tantalum and niobium (Shand *et al.* 1994; Brown *et al.* 2008). These characteristics are consistent with a subduction-related environment in which the sub-continental lithospheric mantle is enriched by emplacement of magmas produced by hydrous melting in the underlying asthenospheric mantle wedge (Macdonald *et al.* 1985). Such enriched material may remelt to produce a lamprophyric magma if conditions are suitable.

Figure 8 Thin section view of the vogesite specimen shown in Figure 5. This PPL view shows brown pleochroic amphibole phenocrysts in a low relief groundmass. Between crossed polars, the groundmass can be seen to comprise relatively unaltered feldspar, with an excess of alkali feldspar over plagioclase (field of view = 9mm × 7mm).



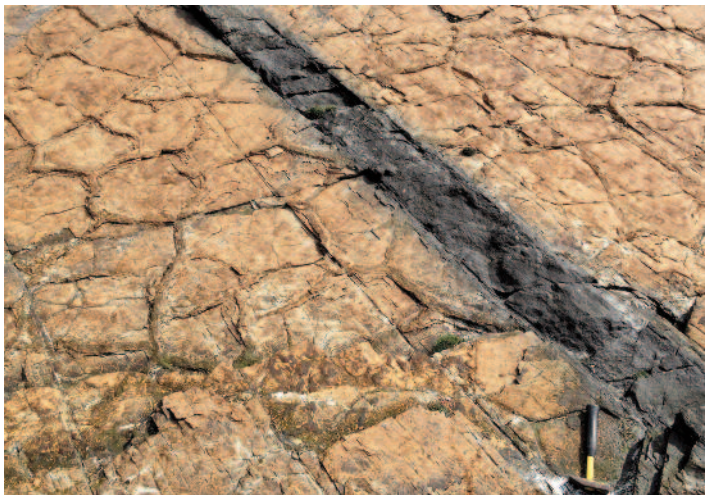


Figure 9 A camptonite dyke intruded into Devonian flagstones that show casts of desiccation cracks — foreshore, Birsey, Mainland, Orkney.

Melting by adiabatic decompression during regional extension has been suggested as the origin of the Devonian-Carboniferous alkaline lamprophyre province in Scotland (Lundmark *et al.* 2011). A similar mechanism has been suggested for the Caledonian calc-alkaline lamprophyre province (Vaughan 1996; Brown *et al.* 2008). An alternative mechanism for these Caledonian lamprophyres was proposed by Atherton and Ghani (2002), who applied the 'slab breakoff' model of Davies and von Blackenberg (1995). In this model (Fig. 10, *opposite*) enriched subcontinental lithosphere is melted by heat conduction from the impinging hot asthenosphere. Migration of the resulting lamprophyric magmas into the overlying continental crust may provide a heat source for the generation of crustal melts that contribute to the formation of the associated granites.

Conclusion

The lamprophyres comprise a fascinating group of rocks; however, their study in hand specimen and thin section can often be frustrating if the primary mineralogy has been significantly altered. There has been significant progress in understanding lamprophyres since the seminal work by Nick Rock and co-workers in the late 1970s, which culminated in the publication of a monograph (Rock 1983b). A comprehensive review to update this monograph is, perhaps, overdue.

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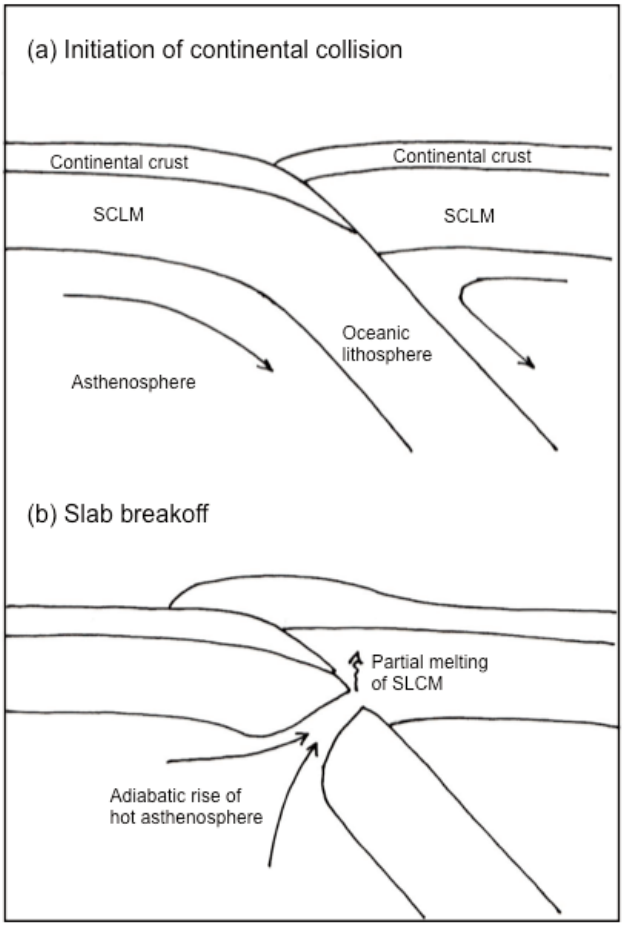
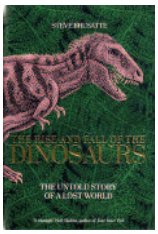


Figure 10 The slab breakoff model of Davies and von Blackenberg (1995): (a) Subduction of dense oceanic lithosphere, together with the attempted subduction of buoyant continental lithosphere, develops extensional forces in the subducting slab (SCLM = Subcontinental lithospheric mantle); (b) The extensional forces may be sufficient to tear the slab, which detaches and sinks into the asthenosphere; the gap produced is filled by hot upwelling asthenosphere, which impinges on the SCLM and may cause partial melting.

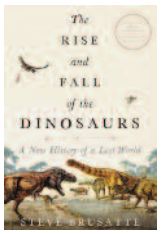
Book review



Brusatte, Steve 2018 *The Rise and Fall of the Dinosaurs: the Untold Story of a Lost World*. London: Macmillan. (ISBN: 978-1-5098-3006-0; 404pp; hardback £20.00, paperback £15.03 on Amazon)

Bracketed by the mass extinctions of the end Permian and end of the Cretaceous, the age of the dinosaurs coincides with the 180 million year Mesozoic Era. Steve Brusatte's story covers that time — from the probable burrow-living dinosaur ancestors to the final extinction of dinosaurs by the Chicxulub asteroid impact and the later evolution of birds. But the book is more than the story of the dinosaurs: it is the story of the development of a science and of the evolution of Steve Brusatte from 'dinosaur-obsessed high schooler' to leading palaeontologist.

The book is divided neatly into chapters, which cover the various stages in the rise and fall of this once-dominant clade. Brusatte takes us from viewing evidence of the Siberian Traps generated extinction in a Polish Quarry to Gubio in Italy in the presence of Walter Alvarez. Along the way he manages to provide an insight into geology and plate tectonics as well as the development of palaeontology. The book also covers his development as a research scientist and the wide circle of colleagues with whom he worked.



In particular he explains how the dinosaurs evolved and developed the characteristics that made them so successful, while also explaining how he used new technology and statistical techniques to solve problems in dinosaur physiology and evolutions.

The Rise and Fall of the Dinosaurs is by no means a formal textbook, and Brusatte writes in an easily read style bringing the subject alive and communicating his own enthusiasm. His account of the Chicxulub impact ("It was the worst day in the history of our planet…") is gripping. Rather than provide the usual bibliography he has elected to include a final chapter: 'Notes on Sources', explaining that his main source is his own work, although there are many other researchers' works also cited. However, the notes are extensive and include supplementary material and sources with full information to enable the reader to find more information. I feel that the text is rather let down by poor, monochrome photographs, although the Todd Marshall line drawings at the beginning of each chapter are works of art. In his prologue Steve expresses his intention to tell the story of the dinosaurs and how palaeontologist have pieced that story together — an intention he more than fulfils.

— Mike Hermolle, MSc Earth Science (Open)

Book review

Hone, D. W. E., Witton, M. P., and Martill, D. M. (eds) 2018 *New Perspectives on Pterosaur Palaeobiology*. London: Geological Society Special Publication 455 (ISBN 978-1-78620-317-5; 232pp; hardback £90, Geol Soc Fellows £45, other societies £54)

Pterosaurs have interested me since I had a 'five-minute chat' about pterosaurs with an enthusiastic palaeontologist at the Royal Tyrell Museum that lasted just over an hour! It certainly seemed like five minutes to me. The name Witton had cropped up several times in our conversation and his name was front and centre on this book together with Hone, who is an acknowledged leading authority on Jurassic and Cretaceous dinosaurs. Martill is another acknowledged prominent palaeontologist.

The book is a collection of papers presenting aspects of up to date research into pterosaurs. Although I have been taking slightly more than a passing interest in Early Cretaceous Chinese feathered avialan and non-avialan theropods, I must confess that I was not aware of most of the research presented in this book. I did not read the book in order. I read it as the papers appealed to me. I did find some of the book a slightly difficult read, but that was because of my failing, not the failings of the book. I thoroughly enjoyed discovering about the enlargement and reshaping of the rostrum as males approached and attained sexual maturity, details of dietary preferences and foraging strategies. In this brief review, I cannot hope to give a summary of all of the research papers in it, but I will pick out a sample of the papers that can serve to 'give the flavour' of the book. I chose the first because I have a background in flying and the capabilities of wings is within my 'comfort zone'.

Colin Palmer looks at the mechanical properties of the pterosaur wing membrane. This subject is not usually an 'easy read', but Palmer explains the technical details simply and clearly. Normally pterosaur wing membrane preservation is poor, and the available fossil evidence does not enable reconstruction of its properties. However, the advent of CT scanning has made it possible to construct high-fidelity structural models of the wing because the actual fossil record for the wing bones is relatively good. Using diagrams, drawings and CT scans Palmer manages to explain the discoveries. The mechanical engineers among you can see the methodology if you wish, but I must admit that I largely ignored the occasional equation and just accepted the explanations as presented.

If you like looking at bones, teeth and jaws you will definitely enjoy the presentation of pterosaur finds from the Upper (Late) Jurassic Morrison Formation from Wyoming. M. A. McLain and R. T. Baaker use pictures of the finds, as well as excellent drawings, to explain the finds. No technical mechanics here; it is accessible to anyone with a moderate knowledge of fossils.

In another paper, Stanislas Rigal, David M. Martill and Steven C. Sweetman describe a new pterosaur specimen found in the Upper Tunbridge Wells Formation (Cretaceous) in southern England. This is just the third record of pterosaurs in this formation. As before, the use of photographs as well as excellent illustrations makes it an interesting read. They also include a simple map of the location, with the geology superimposed to give the map a familiar, accessible feel, especially as there are simplified stratigraphic columns, too. If the name Sweetman sounds familiar, look up the recent discovery of a mammal in the very earliest Cretaceous rocks in Durlston Bay near Swanage. He identified the teeth and forced a rewrite of the history of mammal evolution.

Many of the other papers describe new finds in various formations. The standard of pictures, illustrations and figures throughout the book is superb. The papers are accessible for someone with an interest in fossils or even the development of flight in birds. I have learned a lot from this book; I intend to read it again and learn even more.

— Colin Morley, OUGS Branch Organiser, Wessex Branch

OUGS Field trip to Hawai´i 2018

lead by David Rothery, Scott Rowlands and Sarah Fagents

Susan Barr, Audrey Brown, Jane Browning, Chris Daniel, Pam de Boer, Mellissa Freeman, John Hammond, Stuart Monro, Sally Munnings, Kate Nursey, Alan Painter, Deborah Parke, Carolyn Pascall, Chris Phillips, Marion Phillips, Oliver Strimpel, Tony Wallbank and Pete Wood

Figure 1.1 View from top of Diamond Head of coral reefs.

Figure 1.2 View of Honolulu, sea and coral reefs from Diamond Head.

Day 1, May 6: Diamond Head

Sally Munnings; photos by Sally Munnings

Our first trip out on Oahu was to Diamond Head on a very hot sunny morning. This is a well-known local landmark, which is very popular with tourists. It is formed of volcanic tuff and is part of the system of cones, vents and their associated eruption flows that are collectively known as the Honolulu Volcanic Series, eruptions from the Ko´olau Volcano that took place long after the volcano formed, so in the post shield phase. It is therefore much younger than the main volcanics and is estimated to be *c.* 500,000 to 400,000 years old. The broad saucer shaped crater was formed *c.* 300,000 years ago during a single explosive eruption.

Due to its popularity, when we arrived we could not get into the car park but had to park some way off so the drivers dropped us off and walked back up. We went into the Visitors Centre and had a quick look around before setting off on the walk up to the top. This was across the crater and then up the wall of the crater on a zig-zag path for a fair distance. There were many features showing the deposition of the tuff material alongside the path.

At the end of the path was a tunnel and after the tunnel a set of more than 100 steps! This was not for the fainthearted. Most of us took a rest at the bottom of the steps and a longer rest at the top! After these steps came a shorter tunnel into a fortified area — due to its height it was used as a fort at one time in the history of the Island. However, once out of this area the view was stupendous — looking down at Honolulu and over the coral reefs in the sea around the Island (Figs 1.1 and 1.2).

We came down different steps to the bottom, where we sat enjoying the shade and watching the birds and mongooses (Fig. 1.3).

An excellent introduction to the volcanics of Hawai´i. This was followed in the afternoon by a visit to the University of Hawai'i and an introductory talk.

Day 1, May 6: Introductory Lecture at the University of Hawai´i by Peter Mouginis-Mark

Pam de Boer and Susan Barr

Hawai´i is an island chain that sits mid-Pacific over a mantle 'hotspot'. The tectonic plate moves from the south-east to the north-west, that is, the island in the north-west of the chain, Kaua´i, is the oldest and the island to the far south-east of the chain, Hawai´i (otherwise known as Big Island) is the youngest. Each island grows from the seafloor as a submarine volcano at the place where Kilauea volcano on Big Island is now forming.

Figure 1.3 Mongoose at Diamond Head.

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The formation of the islands goes through various stages, i.e. submarine stage, subaerial shield-building stage, caldera stage, post-caldera stage and erosional stage, followed by rejuvenation stage, although not all volcanoes undergo this last stage, i.e. Wai´anae Volcano on Oahu.

Oahu has Wai´anae Volcano on the western side. This is the oldest, from 3.9–2.8Ma. On the eastern side of the island is Ko´olau, which is 2.9–2.1Ma with a rejuvenation stage dated 50–30ka. Both have undergone an erosional stage and massive landslide collapse.

On Big Island, Kohala, dated 500–300ka, is the oldest volcano and no longer active. Mauna Kea is dated 380–10ka and is in the post-caldera stage of its life cycle. Glacial deposits can be found at the summit and the volcano has been subject to oceanic landslide. There are many cinder cones on Mauna Kea, which are the result of high lava fountains. Hualalai is dated 130ka and last erupted in 1801. Mauna Loa, dated 540ka to the present, has a large summit crater, indicating that it is in its caldera-forming stage. It is the largest active volcano on land in the world. Kilauea is the youngest of the five Big Island volcanoes (100ka to present) and is in the shield-building stage. Most of the eruptions on Kilauea are located along areas of weakness called 'rift zones'. Rift zones are common features of Hawai´ian volcanoes and they are also on Mauna Loa and the other volcanoes on most of the Hawai´ian islands.

The original volcano on Kaua´i (5.1–3.6Ma) was once a much bigger volcano than it now is. A giant landslide took away three-quarters of this volcano to the east. The western side of Waimea Canyon forms the avalanche scarp slope. Later a second volcano developed and built lavas, which almost filled the depression. The old caldera of this second volcano is the Lihu´e basin. This second volcano may also have suffered avalanching to the east.

Day 2, May 7: Honolulu Volcanic Series, including Hanauma Bay, Kolo crater and Makapu´u

Audrey Brown and Stuart Monro; photos by Audrey Brown

Some locations and background are in the *Southeast O´ahu Geology Field Trip Guide*.

Figure 2.1 Scott Rowlands gives an overview of the geology of Hawai´i at the start of the day.

Figure 2.2 Small volcanic bombs deforming the ash layers.

The day started with an overview of the geology of O´ahu by Scott Rowlands drawing in the sand (Fig. 2.1). Those standing by the sea are looking at the island in its N–S orientation. The island is constructed of two shield volcanoes (1–3Ma) — the western third is Wai´anae and the eastern two thirds is Ko´olau. Once a Hawai´ian volcano has moved off the hot spot, and after much erosion, it often undergoes a rejuvenation, producing lavas (600ka) that are alkalic (high in Na and K, low in SiO2), as well as tuff cones, scoria cones, etc. The rejuvenation stage volcanism on Ko´olau is called the Honolulu Volcanic Series. Not all the rocks were volcanic and the lowered sea level *c.* 10ka associated with northern hemisphere glaciation produced blown sand (aeolianite) with evidence of plant roots.

From Pu´u o Kaimuki, standing on a Honolulu Volcanic Series vent, a number of Hawai'ian shield volcanoes are visible. The Kaimuki vent was formed by an eruption, which was poor in water and volatiles, and a 'dry' eruption. It is younger than Diamond Head, which was formed during a hydromagmatic eruption with water present.

Lana´i Lookout is on the southern flanks of the Koko and Kahauloa craters and has material derived from both craters. The volcanoclastic sediments show evidence of explosive, hydromagmatic volcanic activity with each explosive event sufficiently violent to fragment lava into sand-sized particles. Evidence is also present of volcanic bombs penetrating and deforming the ash (Fig. 2.2) and of fragments of coral being picked up and incorporated into the volcanoclastic sediment (Fig. 2.3, *opposite*)

Figure 2.3 Large fragments of coral (pale areas) have been incorporated into the volcanic ash.

At Sandy Beach (reputed to be the second most dangerous beach in Hawai'i) there was a feature that superficially looked like a 'tumulus' (Fig. 2.4). According to the USGS "A tumulus is created when the upward pressure of slow-moving molten lava within a flow swells or pushes the overlying crust upward." However, the sea having neatly dissected this feature, the internal structure was not the expected solid lava but was composed largely of lava rubble making it incompatible with the tumulus hypothesis.

Figure 2.4 Lava fragments inside the crust of lava, so not a tumulus.

Makapu´u Lookout is the end of the Koko fissure. The far island, called Manana (Rabbit Island), is a tuff cone that was erupted on land. The nearer island is Moku Hope, the remnant of a scoria cone and lava flow (Fig. 2.5).

Figure 2.5 In the far distance, Rabbit Island, a tuff cone, and slightly closer, Moku Hope, part of a scoria cone and lava flow.

Figure 2.6 View from Nu´uanu Pali Lookout. The marshy area in the centre represents the remains of a caldera.

Nu´uanu Pali Lookout looks out across what was the centre of the Ko´olau volcano, corresponding to the position of the Kawainui marsh (Fig. 2.6). The evidence for this is a significant gravity high, indicating the presence of a dense former magma chamber at depth. From this point, the orientation of the lavas can be determined with the boundary between slightly inward dipping and steeper outward dipping lavas defining the edge of the caldera.

Day 3, May 8: Wai´anae Volcano — shield and post-shield volcanism

Mellissa Freeman and Kate Nursey; photos by Mellissa Freeman

Wai´anae Volcano

We started the day's activities just outside of Wai´anae, to get a general overview of the post-shield volcanism of the Wai´anae Mountains. These are along the west and south-west of Oahu and at one time the Wai´anae shield's summit caldera was *c.* 4.5km wide. The Wai´anae mountain range has a south-to-north spine, which is made up of tholeiite basalt lava flows cut across with more resistant dykes (Fig. 3.1).

Figure 3.1 First stop of the day just outside of Wai´anae.

Our first stop was looking up axis of the old rift zone. In the distance you can see a young scoria cone *c.* 2.97Ma. This is not a rejuvenation event cone but has been dated back to the shield-building stage. There were two main volcanic stages: the first, and main, event was the building of the shield volcano; then there was a gap of many years — from a few years to many thousands of years— before the next stage, which was the rejuvenation stage, when the volcano reactivated. This was when the majority of the scoria cones were formed. (There can also be spasmodic smaller events between these two main stages.) The area is subject to slump erosion of some of the larger blocks and is not typical of Hawai´ian deflated rift zones (Fig. 3.2).

The lava flows in the second photo are dipping towards the SE, indicating, along with their location, that they were erupted outside of the old caldera. The lavas at the base of Pu´u Heleakalā have been dated to *c.* 3.7Ma.

Figure 3.2 Pu´u Heleakalā in the Nanakuli valley along Farringdon Highway.

Figure 3.3 Mauna Kūwale ('mountain standing alone') the small peak in the centre of the photograph.

Our second stop was on the edge of a fenced Naval Comms area, just off the Farringdon Highway. There is a gravity anomaly here, which indicates the location of the magmatic centre of the Wai´anae Volcano. At one point this area would have been *c.* 3km high, which is difficult to imagine now. The orientation of the rocks all dip away from the centre with hills all around (Fig. 3.3).

The composition of the rocks on Mauna Kūwale are slightly different: the top layers are rhyodacite, which is *c.* 3.3Ma. These layers probably formed as a result of crustal melting; and the rhyodacite layer is overlain by a thin layer of basalt, which is compositionally different, and indicates that there was a regime change between pre- and post-caldara formation.

Scott Rowlands pointed out that a strange little diversion volcano went through this area, its presence only revealed where it has been eroded.

Our third stop was at the cave at Kāneana, which means the 'cave of the God Kāne' (Fig. 3.4) It is also known as Makua Cave. This is a sea cave rather than a lava tube.

There are a lot of dykes visible here, all heading towards the sea along the axis of the NW rift zone (Fig. 3.5).

Figure 3.4 Some of the group enjoying the shade inside the cave.

The cave was cut when sea level was *c.* 30m above present, *c.* 500ka during the Ka´ena highstand. Remnants of older fragmented country rock can be found on the beach just across the road from the cave. Just as you enter the cave there are large rounded boulders (6.7m high) that have been cemented in place by lithified sand. Just above these boulders is a layer of crumbly clinker, followed by a layer of basalt (Fig. 3.6, *overleaf*). The dykes have a tholiitic composition similar to the country rock (Fig. 3.7, *overleaf*).

Stop 4, after lunch, was to the end of the Farringdon Highway. The beach at Keawa´ula is an old raised reef terrace made up of fossilised corals, coral rubble and shell fragments (Figs 3.8 and 3.9, *overleaf*). It would have formed during a highstand of sea level. Just above the corals is a layer of with calcareous sandstone. There was a period of sea level rise here and the reef was built. Sea level then dropped and the sandstone was deposited. Sea level then rose again. In places, there is evidence of wave-cut notches.

Figure 3.5 Dykes cutting through the rocks near the cave entrance.

Figure 3.6 With Chris Phillips for scale, showing the height of the cave as you enter. Dykes are visible along with the basaltic layer half way up the photograph.

Figure 3.7 Close-up of one of the dykes cutting through Kāneana ('cave of the God Kāne'), or Makua Cave.

Figure 3.8 The group inspecting the fossilised corals on Keawa´ula beach.

Figure 3.9 Fossil corals from Keawa'ula beach.

We then walked north along the crest of an old raised reef terrace next to the shoreline, then dropped back down to the beach to look at the metre-wide dyke with columnar jointing (Figs 3.10 and 3.11).

Day 4, May 10: Big Island — Hawai´i Volcanos National Park and Kilauea

Marion Phillips and Chris Phillips; photos by Chris Phillips

This was to be our first full day on the island Hawai´i, commonly known as Big Island. This, the youngest island of Hawai´i group, comprises five shield volcanoes that have built up from the ocean floor, which is some 4.5km deep in this area of the Pacific Ocean. Earth's largest volcano, Mauna Loa on Big Island, projects more than 4km above sea level (so its top is *c.* 9km above the deep ocean floor). Shield volcanoes are the result of multiple eruptions, most of which have produced fluid basaltic lavas, which flow and harden. Due to the low viscosity of these lavas,

Figure 3.10 Dyke crossing towards the sea, following the direction of the rift zone.

Figure 3.11 Close-up of the columnar jointing in a dyke on the beach.

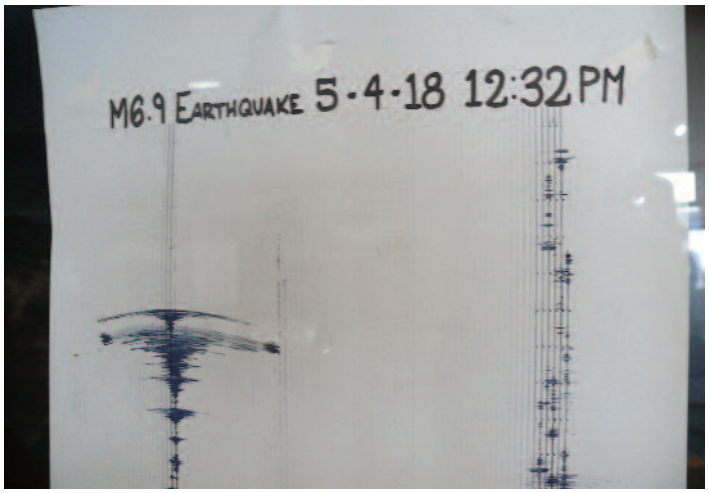


Figure 4.1 Volcano Observatory Seismic 6.9 trace on 4 May 2018.

flows are relatively thin and travel far, building up slowly to produce a volcanic profile like that of a shield lying on the ground.

We had a five-day stay on Big Island, and for many of us the highlight was to be our visit to the Hawai´i Volcanoes National Park, home of the youngest and most active volcano, Kilauea.

Since 1983, the Kilauea volcano on Big Island has been actively erupting. It has produced a cubic mile [4.17km^3] of lava, resurfacing 48 square miles [124.32km^2]] of land. From early May 2018, however, the eruption intensified significantly. On May 3rd, the Kilauea lava lake at the caldera pit crater of Halema´uma´u began to empty as the lava level dropped and a number of new lava vents opened up beneath the summit along the East Rift Zone. Seismic activity had increased from April 30th, which culminated in a strong earthquake of magnitude 6.9 on May 4th (Fig. 4.1).

By May 10th the number of erupting fissures had increased to nine and the level of lava at the summit was continuing to drop precipitously towards the water table. This raised fears of a possible violent phreatomagmatic (steam/lava explosion) eruption, which would be likely to occur when ground water flows above the hot rock. The Hawai´i Volcanoes National Park therefore announced the closure of the park to the public from May 11th until further notice and although still open on May 10th, access to much of the park was severely restricted.

Figure 4.2 Sarah Fagents sets the scene at Volcano Observatory relief map.

As a result of these developments, May 10th was our only opportunity to view the Kilauea volcano at close hand. Our guide for the day was Sarah Fagents from the University of Hawai´i, who gave us an informative talk about Big Island and Kilauea, rearranged our schedule to enable us to see as much as possible in the time available, and pointed out areas of interest throughout the day (Fig. 4.2).

Unfortunately, the morning in the Park was wet and foggy, so most of us were unable to see the now empty crater at Halema´uma´u. Despite this we met with Don Swanson, a geologist with the U.S. Geological Survey's Hawai´ian Volcano Observatory, who gave us a presentation on Kilauea's explosive history. For the past two centuries, Kilauea has erupted gentle lava flows and infrequent high lava fountains — activity that has destroyed property, but has not been particularly hazardous to people, except on rare occasions. Research has revealed that Kilauea has not always been so benign. During the past 2,500 years, Kilauea's volcanic activity has alternated between periods of dominantly effusive and dominantly explosive eruptions. Effusive activity, like that of Kilauea's 2018 ongoing east-rift-zone eruption, makes up only 40 per cent of the volcano's eruptive history, while periods dominated by explosive eruptions from a deep caldera make up 60 per cent of the time.

Figure 4.3 Don Swanson at terrain cross-section adjacent to the Jaggar Museum.

Don illustrated his talk with a cross-section through the terrain adjacent to the Jaggar Museum, close to the rim of the Kilauea caldera, and we were able to examine the various layers from eruptions dating back from the 1600s to the most recent explosive activity in 1921. There was evidence of ash, cinders, reticulite, pumice and scoria in some of the eruptive layers, indicating explosive activity (Fig. 4.3). The most famous of these eruptions was a summit eruption in 1790 when a number of members of the Hawai´ian army were killed.

In the afternoon we walked along the Napau Trail to look at the 1969–74 lava flows that formed the Mauna Ulu satellite shield. Here, many features were evident including a fire-fountain fissure with a spatter rampart 50–75m high on one side (upwind) and the lava flow on the other side of the fissure (downwind).

We also saw many tree moulds, which form when pahoehoe lava flows through a forest. A skin of lava solidifies around the trees up to the level of the flow surface and when the eruption

Figure 4.4 Sarah Fagents explains tree mould formation at a collapsed lava surface.

Figure 4.5 Tree mould with new life emerging.

wanes, the lava level drops as lava drains away and gas-lava separation takes place, leaving a mould of the tree standing above the collapsed lava surface (Fig. 4.4). Of course, the trees always die and usually burn, but the organic matter sometimes left behind acts as place where new plant seeds can grow (Fig. 4.5).

The Napau Trail (Fig. 4.6) also took us past Pu´u Huluhulu cinder and scoria cone and through a´a and pahoehoe lava flows to the Makaopuhi Crater (Fig .4.7).

Figure 4.6 Crossing the Napua Trail lava fields to the crater edge.

Figure 4.7 Makaopuhi Crater edge in the mist.

Day 5, May 11: Hilo to Waimea

Chris Daniel and Alan Painter

Our Day 5 trip was a 100-mile [161km] road trip in convoy around the south side of Big Island on the southern flanks of Mauna Loa, with frequent field stops along the way.

We travelled a surprisingly straight, but gently undulating road through a strange black, alien landscape. Low-sloping lava fields of lithified a´a on both sides of the road, stretching a mile or two down to the sea on our left, and two or three miles [3.2–4.8km] inland on our right. Patches are semi-vegetated with short stubby bushes, but the bulk is unvegetated, raw rock.

At 11:00 we had a roadside stop to view the newly active fissures on Big Island, along the rift zone running north-east from Kilaluea crater. From the road we have a distant view of the gas plume rising several thousand feet [300+ m] into the air, with a pink brown haze spreading downwind. There was a faint sulphurous smell in the air.

At 12:00 we reached Punalu´u Beach (Fig. 5.1, *overleaf*). This is the best example of a black sand beach on the island. The sand is produced by quench grinds — slippery layers of lava entering the sea. The layers produce unstable ‘lava deltas’.

At 12:30 we reached a roadside park, for a view of the Ninole Hills, where there is a lighter grey ash exposure of Patida ashfall. The exact origin

Figure 5.1 Punalu´u 'black sand' beach (photo by Chris Phillips).

of the hills is not established, but there are two theories: an earlier separate volcano; or an earlier phase of Mauna Loa.

At 13:00 we arrived at Whittington Beach Park at the old Puna Ahu fishing harbour, now destroyed by a tsunami and subsidence. In the exposed cliff-side, there is a good example of a lava tube, the so-called 'MJ exposure' after its similarity to Mick Jagger's tongue (Fig. 5.2). It shows thermal erosion of its substrata. Lava within a tube is very well insulated and can stay hot for up to 75 days. Here we had lunch under the hibiscus trees with noddy and cardinal birds for company. Voted best lunch stop of the field trip.

At 14:20 we had a roadside location stop at the 71 Mile Marker, to examine channelised a´a flows from an 1868 eruption vent on the flanks of Mauna Loa. An estimated 120 million m^3 [4,237,764,000ft^3] erupted in five days. Here, we found abundant examples of picrite basalts with prominent olivine crystals (Fig. 5.3). Their chemical origin was from lower sections of the magma reservoir.

Figure 5.2 Whittington beach park, MJ exposure Lava Tube (photo by Mellissa Freeman).

The rate of settling of these crystals in the erupted lava has been used to estimate the viscosity of the lava, which has been calculated as *c.* 600 Pascal secs (peanut butter is *c.* 250 Pascal secs; 1 Pa = 1kg × m^{-1} × s^{-2}). Here there is also a good exposure of a cross-section through a levee, showing overbanking and multiple layers of red oxidised basalt (Fig. 5.4, *opposite*).

We reached Mile Marker 75 at 15:00, a scenic point overlooking Ka Lae (South Point), with a view of a branch of a 1907 lava flow, 10km [6.2 miles] from its vent. Here new lava had over-flowed an existing scarp. The bumps near the seashore are known as littoral cones, formed by explosions at the lava-sea interface. The oceanite and picrite basalts present in the clinker layers are thought to come from magma reservoir sludge.

Figure 5.3 Picrite basalt with prominent olivine crystals (photo by Chris Phillips).

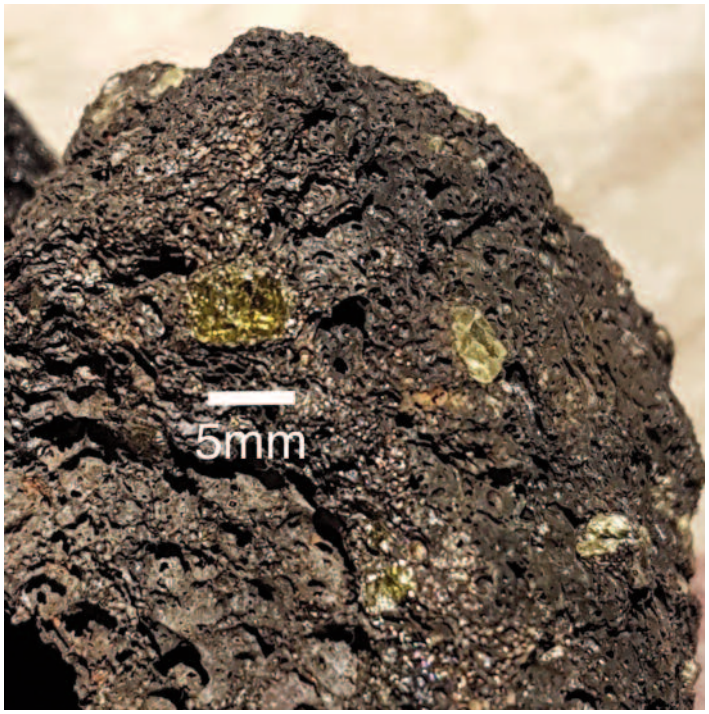


Figure 5.4 Cross-section through levee showing overbanking and multiple layers of red oxidised basalt (photo by Mellissa Freeman).

We drove north along the west coast, rounding the north-west corner of the island. The vegetation changed dramatically from semi-arid shrub on the west side with *c.* 10in [254mm] of rain annually to lush forest on the east side with 10–15 times as much rain. The rainfall pattern is determined by the prevailing north-easterly winds that form thick clouds on the windward side of the islands. At the end of the road at Polulū Valley overlook we could see the steeply incised north-east coastline. The very steep geomorphology here may be related to a large landslide towards the end of the Polulū series activity. The landslide may also have blocked the stream paths, causing them to cut new, steep channels that created the deep indentation of the coast here.

Some of the group walked down the slippery path to the Polulū valley, where a 140ka lava flow of the Hāwī volcanics is visible on the bank of the valley. Undeterred by the strong current warning signs, a few group members cooled off in the choppy surf.

At 15:40 we had a cultural stop at the Hawai´ian native equivalent of a 'naughty step'. This was the Pu´uhonua o Hōnaunau National Historical Park. The guide told us that this was an old Hawai´ian place of refuge. If you had done something wrong, you could escape serious punishment by coming and staying here for a period. More like a 'sin bin', I guess, than a naughty step!

Day 6, May 12: Kohala volcano

Oliver Strimpel; photos by Oliver Strimpel

We devoted the better part of this day to Kohala, the oldest of the five volcanos on Big Island. It occupies the north-west corner of the island, farthest from the hotspot and diametrically opposite to the current volcanic activity at Kilauea and the still submerged Lō´ihi. All its exposed flows are younger than 780ka, with the shield stage strata, called the Polulū series, having radiometric ages of 450ka–320ka. The Hāwī post-shield stage volcanics overlie the Polulū series and mostly date from 260ka to 140ka. Kohala has a NW–SE axial rift zone whose orientation is thought to have been determined by an older offshore volcano that buttressed Kohala on its south-west flank. The rift zone was active both during the shield-building stage as well as during the post-shield alkalic phase. One can trace the rift zone to the south-east beneath Mauna Kea, and as a submarine ridge beyond Hilo on the east coast.

We stopped at Māhukona Beach Park, the site of an old harbour built to export sugar, to look at a tholeiitic flow from Kohala's shield-building stage (Figs 6.1 and 6.2). Unusually for shield-stage lavas, this flow contained large phenocrysts of pyroxene and plagioclase. We spotted olivine and amphiboles as well. The ridge of Maui's Haleakala was clearly visible *c.* 50 miles away across the sea to the north-west.

Figure 6.1 Mahukona Beach Park – Kohala shield stage (Pololū Series) flow.

Figure 6.2 Indented coastline along Kohala's north-east flank.

Figure 6.3 (above) Examining the Ben Moorite above Waimea.

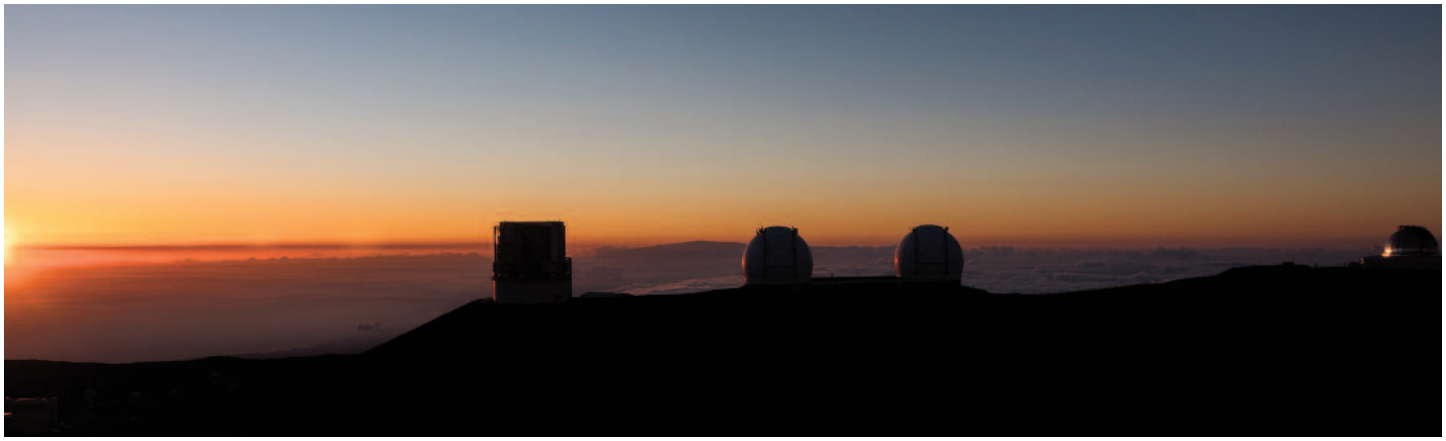
We took the ridge road back to Waimea, stopping off at a scenic overlook with a large exposure of Ben Moorite, a very high silica alkali andesite. We identified olivine, altered plagioclase, amphibole, and pyroxene phenocrysts in the roadcut there (Fig. 6.3). We could make out Hualālai (8,271ft / 2,521m), Mauna Kea and the astronomical observatory complex (13,796ft / 4,205m) (Fig. 6.4), and Mauna Loa's summit above the cloud layer (13,679ft / 4,169.4m).

In the evening, most of the group went to the Mauna Kea Visitor Center to explore a cinder cone there and look at the spectacular night sky (Figs 6.5 and 6.6, *opposite*). Despite the park rangers' dire warnings that the vehicle was inadequate, one carload drove up the rutted dirt road to the summit to see the sunset and the glaciated geomorphology.

Figure 6.4 (middle) Mauna Kea, with numerous post-shield stage cinder cones on an otherwise nearly perfect giant cone; the portion visible above the clouds is c. *25 miles [40km] across.*

Figure 6.5 (bottom) The Mauna Kea Visitor Center (lower left) and cinder cones just above it.

Figure 6.6 (opposite top) Mauna Kea summit: from left, the Subaru 8.2m [27ft] optical telescope; the twin Keck Observatory telescopes, each with a 10m [33ft] multi-mirror array; and the 3m [10ft] Nasa Infrared Telescope Facility, first built to support the Voyager missions.



Day 6, May 12: Evening visit to Mauna Kea Visitor Center and Observatory

Sally Munnings

Most of us decided to go back to the Observatory in the evening to see the stars. We had to get there early in order to get into the car park as it was extremely popular. One car drove up to the top — more than 13,000ft [*c.* 4,000m]. The rest of the group spent the time in the shop while waiting for darkness to fall, walking up the cinder cone opposite to see the sun setting and drinking hot chocolate — it was quite cold after the sunset at the Visitor Center's altitude of over 9,000ft [*c.* 2,750m]. While we were doing this, the Observatory staff set up a number of telescopes.

We all got a chance to look through the telescopes at Venus as it rose. After it got dark we could see millions (literally!) of stars. We could also see both the Pole Star and the Southern Cross at the same time, which I found fascinating.

Unfortunately, although we could see the Milky Way, it was fairly faint — this was not the best time of year to see it. It is much clearer at other times.

We finally left at about 10pm to go back to the hotel.

Day 7, May 13: Kaumana Cave, Puu Huluhulu, Mauna Loa weather observatory and lavas

Deborah Parke and Pete Wood; photos by Pete Wood

From our replacement base in the north of Hawai´i at Waimea we drove south-east along Highway 200 towards Hilo. The road is known as the Saddle Road because it follows the low ground between Mauna Kea to the north and Mauna Loa to the south. Five miles west of Hilo we reached the Kaumana Cave (N19° 41´ 13´´, W155° 07´ 51´´) (Fig. 7.1).

Figure 7.1 More hats than at the royal wedding. Some of the team ready to descend into the Kaumana Cave.

The cave entrance is a collapsed skylight in a lava tube formed in the 1881–2 Mauna Loa eruption (Fig. 7.2). It is *c.* 10m high and is said to be nearly a kilometre long, but we restricted our inspection to the 100m nearest to the entrance. The walls of the cave are terraced, marking successive stages in the lowering of the cave floor as the pahoehoe magma flowed along (Fig. 7.3). A torch shone up to the roof of the cave revealed not only curtains of tree and shrub roots searching for moisture, but also separate patches of gold and silver metallic crystals encrusting the rock. Where the gold crystals were accessible at eye level they proved to be pyrite (FeS_2) but the silver crystals were always out of reach. Given their colour, lustre and situation they may well have been arsenopyrite (FeAsS).

Figure 7.2 (above) Entrance to the Kaumana Cave, a tube in lava from the 1881–2 Mauna Loa eruption.

Figure 7.3 (below) Inside the Kaumana Cave showing the benches formed by successive levels of flowing lava.

Figure 7.4 Lunch in the quarried section of Puu Huluhulu cone, a late stage alkali eruption on the lank of Mauna Kea.

Figure 7.5 Lava bomb beside the cone of Puu Huluhulu.

Returning to the daylight, we were rejoined by two of our vehicles, one of which contained a splinter group of happy geologists who had succeeded in getting airborne in a helicopter trip over Kilauea and had actually seen some red lava issuing from a fissure! The reunited group made its way back north-west along Highway 200 to the junction with the road (the John A. Burns Way) leading up to the observatories on Mauna Kea.

Beside the main highway there is a cinder cone called Puu Huluhulu (N19°411´ 4´´, W155° 28´ 05´´) (Fig. 7.4), part of which has been quarried away for road stone and where we sheltered from the wind and drizzle to have lunch. The quarrying operations provided the opportunity to study the cone's internal structure (Fig. 7.5).

The cinder cone is one of Mauna Kea's late stage alkalic eruptions and it is surrounded by later lava flows from Mauna Loa. The cone formed a virtual island, known as a 'kipuka', in a sea of lava, and trees have found a refuge there. Perhaps this gave rise to the cone's name, as it means 'hairy hill'.

Standing on the summit of the cone, it was clear to see that there were two separate lava flows around its base: a dark brown a´a flow and a later dark grey pahoehoe flow (Fig. 7.6). The latter is the 1935–6 eruption of Mauna Loa, but the former is described as 'prehistoric', meaning, in Hawai´i, that it occurred before the 19th century.

Returning to the base of the cone, we set out across the lava field to examine its surface features. Highway 200, at this point, marks the flattest part of the saddle between Mauna Loa and Mauna Kea, and the 1935–6 eruption stalled and ponded here. The slow-moving lava front cooled and formed a surface crust, but as more lava came from higher up the mountain it inflated the crust, lifting and splitting it like a loaf of bread in an oven — as shown in Figure 7.7.

Figure 7.7 An inflation crack in the crust of the 1935–6 Mauna Loa pahoehoe flow.

Figure 7.6 View to the west from the summit of Puu Huluhulu. Two lava flows can be seen: the dark grey 1935–6 pahoehoe flow from Mauna Loa and the earlier dark brown a´a flow. The remains of a drystone wall can be traced as a diagonal from lower right to the centre of the view.

Figure 7.8 A lava rise pit in the grey pahoehoe flow showing a window into the earlier brown a´a flow.

Figure 7.9 Contact between the later dark grey pahoehoe flow and the earlier brown a´a flow.

There is also one curious feature here: a man-made drystone wall erected across the older a´a flow, but nearly engulfed by the later pahoehoe flow. Inflation of the younger flow had brought its surface level with the top of the wall, so while the flow could not cross the wall it had, effectively, buried it. Here and there in the pahoehoe flow there were depressions, up to a few metres across, that acted as windows through the younger lava to the older a´a lava underneath (Figs 7.8 and 7.9). These windows are areas where the overlying, younger lava did not inflate, and they are known as 'lava rise pits.

Some 300m east of the cone, along Highway 200, we took a small, surfaced road to the south that led up to the weather observatory on the flanks of Mauna Loa. Besides the observatory, at the end of the road there was a laboratory where volunteers underwent isolation experiments in preparation for some future Mars landing — the Hawai´i Space Exploration Analogue Simulation (Hi-SEAS) project. We stopped short of the observatory, beside some radio communication dishes at N19° 350´ 2´´, W155° 27´ 13´´ and, surrounded by the fog of low clouds, set out on a 3km walk down the road across a series of lava fields.

These lavas are mainly pre-1800 AD and, with the effect intensified by the fog, make a barren, almost lifeless, wilderness (hence the Hi-SEAS project). Nonetheless, we discovered many superb lava surface features, including beautiful ropy pahoehoe at N19° 35´ 09´,´ W155° 27´ 24´ (Fig. 7.10), a magnificent tumulus (a cracked mound of uplifted lava crust raised either by the accumulation of gas or by the inflationary pressure of flowing lava beneath the crust) at N19° 35´ 46´´, W155° 27´ 49´´ (Figs 7.11 and 7.12), and a lava channel with raised levées at N19° 35´ 13´´, W155° 27´ 34´´ (Fig. 7.13, *overleaf*). A pit, *c.* 8m across, at N19° 35´ 09´´, W155° 27´ 24´´, with a floor covered in broken fragments of lava crust proved to be the collapsed roof, or skylight, over a lava tube beneath (Fig. 7.14, *overleaf*).

Figure 7.10 Deformation of the soft surface of a pahoehoe lava flow frozen in time.

Figure 7.11 A spectacular multilayer tumulus.

Figure 7.12 Leader Sarah Fagents standing on another tumulus.

Figure 7.13 A channel of dark lava cutting across a lighter brown lava.

Surrounded by such a display of magnificent lava features it is not clear whether it was a matter of exhilaration or desperation that led to the tranquillity of the wilderness being shattered by the sound of the combined voices of the OUGS choir on tour in a rendition of ABBA's song *Knowing me, knowing you, A´a* (apologies to Benny and Bjorn). While it is not known whether the volunteers in the Hi-SEAS laboratory were frantically reporting back to base the discovery of alien sounds from Mars, Dave Rothery is reputed to have vowed to go back to Milton Keynes to take up sedimentology rather than go through that experience again.

On returning to Highway 200, we turned north-west and headed back to our motel at Waimea. As it was Sunday, the town's amenities were closed, but several of our motel rooms had fully equipped kitchens, a couple of which became venues for relaxation. Thanks to all for providing the meals.

Figure 7.14 A collapse pit (skylight) into an underlying lava tube.

Day 8, May 14: Hualālai volcano and Pu´u Wa´awa´a cone

Jane Browning and Tony Wallbank; photos by Tony Wallbank

We spent Monday on the flanks of Hualālai, one of Big Island's main volcanoes, stopping to look at Pu´u Wa´awa´a trachyte cone and investigating the topography resulting from the old lava flows from Hualālai and Mauna Loa, en route to dropping Sarah Fagents at the airport and moving to our next hotel at Kailua-Kona (Figs. 8.1 to 8.6, *this page and pages 109–10)*.

We could see four of the five volcanoes on Big Island, only Kilauea was out of sight. There were also good views of Maui, the next island to our north.

Figure 8.1 Lava ball with rounded morphology associated with an a´a flow. It would have started marginal to the lava channel, sufficiently ductile or plated with liquid lava.

Figure 8.2 A trachyte flow, with Maui in the distance. This flow was 50–51km long, emptied not from a rift zone, but from a north-east-trending vent some 3,400–2,600m above sea level. It was a 'paired' eruption where a high effusion rate, which lasted for two weeks, produced a'a lava, with high lava fountains at the vent, so releasing lots of gas. This degassing resulted in a change to an effusion of pahoehoe lava, which lasted about 11 months at an average discharge rate of 5m/s.

Figure 8.3 Pu'u Wa'awa'a, pyroclastic trachyte cone, showing water-eroded features. At c. *110,000 years old it predates Hualālai, which has been active for the past 13,000 years. Pu'u Wa'awa'a has remained above all the lava flows that have flowed from Hualālai. It is unusual in that it contains pumice and obsidian.*

Figure 8.4 Obsidian, a glassy, vesicle-free version of trachyte, which was once quarried from the cinder cone.

Figure 8.5 View of the 1775 a´a flow towards the west.

Day 9, May 15: Kaua´i island

Pete Wood; photos by Pete Wood

After a mid-morning flight from Kona airport we arrived in Kaua´i just before midday. The original schedule offered the option of an easy afternoon, but with enthusiasm still running high we opted to head up the north-eastern side of the island towards the northern shore.

Kaua´i is an older island than Big Island. Some five million years ago sub-alkaline basalt flows built up the large shield volcano Wai´ale´ale. A number of very large landslips modified the topography of the island while the shield lavas were being erupted, but this volcanic activity waned around three million years ago. From then until half a million years ago a more modest alkali basalt volcanism prevailed and these rocks, called the Koloa Basalts, formed the landscape that we travelled over towards the north shore.

Figure 8.6 Collapsed lava tube from the 1800–1 pahoehoe flow from Hualāla.

As we travelled along it was noticeable how more verdant the countryside was compared to Big Island. This was a reflection of the greater age of the island and the time that had elapsed since the island was over the mantle hotspot. It also resulted from the island being one of the wettest, if not the wettest, places on Earth, with an annual rainfall approaching 500in [12.7m]. In fact, just a month before we arrived they experienced nearly 50in [1.27m] of rain in one day, setting a record for the USA. Oddly, it did not rain once while we were there.

Our first stop was at the Wailua Falls (N22° 02´ 02´´, W159° 22´ 44´´) where the Wailua River drops some 80 feet [24.4m] over a Kaloa pahoehoe basalt flow (Fig. 9.1, *opposite*). This flow had been confined to the valley of the ancient Wailua River and its lower section is formed of large lava pillows where the flow first entered a waterlogged swamp. The upper part of the flow shows more massive pahoehoe characteristics. The tops of the valley sides are fairly flat, having been built up by successive Koloa alkaline basalt flows, but 1.5km to the north-east the small conical hill of A´ahoaka can be seen. This was a remnant of the older, shield-building, sub-alkaline basalts.

We reached the north shore at Kilauea Point (N22° 13´ 46´´, W159° 24´ 07´´) with its lighthouse and bird sanctuary. On the east side of the point is a small bay (Fig. 9.2, *opposite*) and its eastern headland shows a cross-section through a series of ash and agglomerate layers that once formed a small cone belonging to the Koloa Volcanic Series. This may have been the last volcanic activity on Kauai, as it has been dated to *c.* 15,000 BP. The agglomerates are the result of basalt magma mixing either with seawater or with groundwater to create phreatic explosions.

Next we headed west towards Hanalei Beach, a long beach and not well signposted; all vehicles found the beach, but not the

same location. From our car, at N22° 12′ 25′′, W159° 29′ 54′′, we could see hills to the west, rising to more than 1,000m, separated by deeply incised valleys. This landscape was built up from more than 600m of Koloa volcanics sitting on the sub-alkaline basalt shield lavas of Wai′ale′ale. Intense weathering by the tropical climate and rapid erosion from high rainfall created the incised valleys (Fig. 9.3).

This visit ended our explorations and we drove back to the south of the island to our hotel.

Figure 9.1 Wailua Falls, Kauai. The Wailua River falls over a resistant pahoehoe lava flow, a member of the Koloa Volcanics, the late alkali basalt stage. Below the resistant flow, the falls have cut back into softer flows and ash beds. The peak on the skyline is A′ahoaka, a residual exposure of the main shield building lavas.

Figure 9.2 The bay just to the east of Kilauea Point. The bedded rocks on the headland are layers of ash and agglomerate laid down in a small volcanic cone, part of the Koloa Volcanics.

Figure 9.3 View across Hanalei Beach towards the west. The high hills are formed of Koloa Volcanics and the deep valleys between are the result of intensive weathering and erosion in Kauai's tropical climate .

Day 10, May 16: Waimea canyon and Napali cliffs, West Kaua'i

John Hammond and Carolyn Pascall; photos by John Hammond

Our last day in the field started with a visit to a prominent dyke just north of the junction of routes 550 and 552. The dyke is on the west side of Waimea canyon and was a feeder during the creation of the original shield volcano. This was formed from *c.* 5.1Ma, of numerous lava flows and ash falls called the Napali Formation. The dyke exposure, cut by the road, is *c.* 100m long and 3m wide, roughly vertical, and trends NE–SW. The dyke and the lava and ash flows it cuts show typical tropical laterite weathering to a strong red colour, with spheroidal weathering evident in the dyke (Figs 10.1–5, Fig. 10.5, *opposite*).

Figure 10.1 Dyke looking s-w, admired by OUGS geologists.

Figure 10.2 Barefoot professor being erudite about the dyke.

Figure 10.3 View south-west along dyke on west side of road.

Figure 10.4 View north-east along dyke on east side of road.

Figure 10.5 Spheroidal weathering of dyke.

During construction of the shield a massive caldera and flank collapse occurred, removing the centre and eastern side to below today's sea level, and leaving a high and precipitous scarp, which is now eroded and forms the western side of Waimea canyon. Eruptions continued from roughly the same centre and built a new shield; flows ponded onto the scarp and, now eroded, form the generally less steep and heavily vegetated eastern side of the canyon. The lava flows of this second phase, called the Olokele Formation, became more massive, with thicker flows showing columnar jointing and greater resistance to erosion. The main shield-building phase ended *c.* 4.4Ma. Feeder dykes, mostly trending NW–SE, are evident in quantity on the western (Napali) side of the canyon, but appear to be scarcer on the eastern (Olokele) side (Figs 10.6–10, Fig. 10.10, *overleaf*).

Figure 10.6 (lower left) Dykes feeding original shield on west side of Waimea canyon.

Figure 10.7 (lower right) Dykes on west side of Waimea canyon.

Figure 10.8 (bottom left) East side of Waimea canyon, second phase of shield building after collapse.

Figure 10.9 (bottom right) Waimea Falls and east side, columnar jointing in massive lava flow.

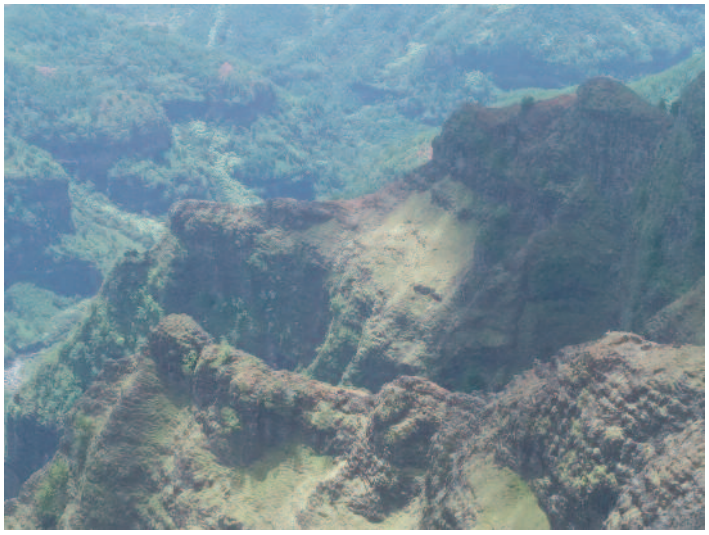


Figure 10.10 View east through ravine in west side (original shield) to east side (second shield).

After our visits to several viewpoints above the western escarpment of the canyon, often accompanied by assorted feral poultry endemic to the island (one group monitors the airport check-in queue) that recognises tourist sites as good feeding opportunities, some of us drove along a rough track to the southern end of the Napali cliffs. These are seriously impressive: very steep and very high, formed by sea (so non-lateritic) erosion of the north-western margin of the original shield. They would once have been even higher, as the island and the ocean floor it rests upon have subsided by *c.* 1km since moving away from the hotspot. The pebbles below the cliffs contain many olivine phenocrysts, derived from the picritic basalt of the Napali lavas forming the bulk of the cliffs (Figs 10.11–12).

Figure 10.11 Napali sea cliffs of original shield, looking north.

Figure 10.12 Picritic basalt pebble with olivine phenocrysts, debris from Napali sea cliffs.

Guidance on submission for publication of work submitted for assessment on Open University modules

from Dr Angela Coe

Senior Lecturer, OU School of Environment, Earth and Ecosystem Sciences

Editor's note: In the past few years several OU students have enquired about writing articles for the OUGS Proceedings*, based on OU course module work they have done. This has raised the issue of publishing module essay material that could jeopardise future students in choices of topics for module research and also exacerbate the increasing problem of student plagiarism at universities. The OUGS Committee therefore sought advice from the OU and Dr Coe agreed to write a set of guidelines for us, which is published below, and for which we are grateful.*

Work that has, or is to be, submitted as part of the assessment for Open University modules (e.g. S209, S309, SXG390, S810) should not be submitted for consideration for publication in the Proceedings of the OUGS or in other publications. This is because of the potential for plagiarism, and because it reduces potential options for future students. It should be noted that if the work was to be plagiarised it raises issues not only for the student who has plagiarised, but also for the author(s) of the article and for the OUGS. We all wish to ensure that future students have the best possible opportunity of completing their assessments independently. The relevant Open University regulation from the *Code of Practice for Student Discipline* (updated July 2017, page 5 of 25) is:

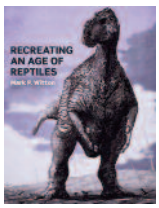
> **SD 1.2 d Serious misconduct enabling plagiarism**
> *Making available, selling or advertising for sale student work in any form or by any means (print, electronic, recording or otherwise) so as to enable plagiarism, whether or not the work includes marks, comments or any other materials produced by a tutor, supervisor or other marker, unless prior consent has been given by The Open University in writing. The offence of encouraging or enabling plagiarism includes the act of posting student work on to any website, whether or not it is done with the intention of enabling or encouraging plagiarism.*

The following articles based on work done for OU assessment are acceptable for submission to the Proceedings of the OUGS:

• A constructive reflection article on *your own experience* of doing the assessment and on how it has helped your progression and understanding. You should ensure throughout the article that it is clear that it is your *experience*. It is not appropriate for the piece to include the views of others, because these are unlikely to be representative, or statements that are a critique of the assessment or of the module.
• An article that describes a new aspect that you did not have the opportunity to explore for the assessment, but that was inspired by work completed for the assessment.
• An article on a geological topic that utilises the skills that you have learned on an OU module.

We strongly encourage all readers to think about utilising the skills that they have learned through OU modules to write engaging materials for the Proceedings of the OUGS.

Book review



Witton, Mark P. 2017 *Recreating an Age of Reptiles*. Ramsbury: Crowood Press Ltd (ISBN 978-1-78500-334-9; 110pp; £16.99)

This book is an enjoyable and at times humorous discussion of the artistic reconstruction of Mesozoic reptiles by palaeontologist and palaeoartist Mark Witton.

The book contains more than 90 colour paintings of dinosaurs, pterosaurs and other Mesozoic flora and fauna, ranging from the mammal-like *Kayentatherium wellesi* to the more well known, famous *Tyranosaurus Rex*.

Witton begins with an overview of his interest in palaeoart from a young age, and the evolving beliefs in the best ways to reconstruct Mesozoic reptiles from the 1980s onwards.

The following 16 short chapters are written around Witton's art, describing the species and explaining the reasons behind the way he has chosen to depict each. While all of the reconstructions are strongly anchored in the fossil evidence, the known paleogeography/environment, and the typical behaviours of extant taxa and better known fossil relatives, Witton has introduced some interesting and sometimes whimsical interpretations of behaviour or colouring. Examples include the rendering of one predatory dinosaur as a giant wood pigeon (dubbed 'supercoo'), a sauropod with a pose and colouring inspired by black-headed gulls (which works quite well), and a depiction of the interspecies adoption of an infant *Triceratops* by a broody *Tyrannosaurus*.

Witton has chosen to portray his reconstructed dinosaurs in real-life settings, often choosing a less well known landscape to those usually seen, and sometimes partially obstructing the view of the animal itself in an attempt to make things more realistic, as if the viewer were present in some prehistoric bird hide.

The paintings vary in colour pallet, some with vibrant depictions juxtaposed against a duller, more washed-out look. This washed-out colour pallet makes the details in some paintings difficult to interpret, most particularly two or three depictions set at night.

After an enjoyable, if somewhat whirlwind and high level tour of various taxa and environments, Witton ends with a rousing entreaty to his peers to not shy away from depicting poorly known animals or unusual ideas — declaring that the dating of the works by subsequent knowledge is "a feature of our trade, [and is] not a problem".

Overall I enjoyed reading this book. From the title I was expecting more technical information on reconstructing images of dinosaurs from fossil evidence, but passages throughout the book did explain the requirements and information that is used. The style was light and funny, and Witton has referenced many further sources or points of interest for further reading.

— Emma Askew, BSc Hons (Open)

Book review

Witton, Mark P. 2018 *The Palaeoartist's Handbook Recreating Prehistoric Animals in Art*. Ramsbury: Crowood Press (ISBN 978-1-785-00461-2; 224pp; paperback £15.99; eBook £16.99)

From the history of palaeoartistry to modern-day techniques, *The Palaeoartist's Handbook* details the effort that goes into producing work that is not only artistically, but also biologically and physiologically as accurate as it is possible to be without actually seeing the animals that are being portrayed.

The perception of the environment in which the animals lived, as well as the plants and other animals upon which they predated, is just as important as the reconstruction of the bones from which the artist produces his craft. Mark Witton demonstrates this admirably with the recreation of scientifically accurate settings in which he places his subjects.

Young, and more senior, readers will enjoy the colourful pictures that grace this book. Geologists will appreciate the accurate depiction of the palaeoenvironment and the understanding that the author portrays of the importance of research.

The Palaeoartist's Handbook is a comprehensive guide to the production of palaeoart, which encourages the observation of present-day animals and birds to understand the way that the underlying structure of musculature impacts on the contours of the fossil animal.

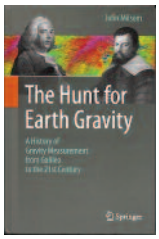
While *The Palaeoartist's Handbook* cannot tell you how to draw a dinosaur, it will explain how to carry out the research that is essential for the depiction of the dinosaur you are trying to draw.

This is a joyous combination of scientific fact and artistic interpretation that has much to offer readers — especially those who are considering work, amateur or professional, as palaeoartists.

This is a 'coffee table book' that will entertain and draw you back time and again. Enjoy!

— Lesley Rafferty, BSc (Hons) Geology

Book review



Milsom, John 2018 *The Hunt for Earth Gravity: a History of Gravity Measurement from Galileo to the 21st Century*. Cham, Switzerland: Springer (ISBN 978-3-319-74958-7; 402pp; hardback £22.50 [due out in paperback July 2019])

Reading this book was like a lovely evening sat listening to someone weaving you an interesting tale through history, personal experience and modern research; it completely befuddled my usual strategy of writing a few words chapter by chapter.

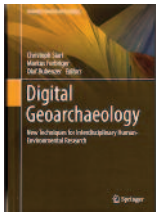
Not only did the author refer to the lives, experiments and feuds of some of the famous, and not-so-famous, scientists, but he quoted his sources and for historical accounts commented on their bias or reliability. He wove in how politics, personalities and other factors affected the work that was done and where.

The Epilogue is the penultimate chapter and it is perfectly reasonable to read to the end of the Epilogue and stop; for those interested in the details Chapter 14 'The Codas' covers vectors, graphs and equations, which provide detail for those who want it without overwhelming anyone who finds this aspect intimidating; and I think that structuring it like this was a very good idea, as it enables a certain amount of adaptation by the reader.

I thoroughly enjoyed reading this book and have recommended it to my cousin already.

— Helen Coombs, BSc Hons (Geosciences)

Book review



Siart, Christoph, Forbinger, Markus, and Bubenzer, Olaf (eds) 2018 *Digital Geoarchaeology: New Techniques for Interdisciplinary Human-Environmental Research*. Cham, Switzerland: Springer International (ISBN 978-3-319-25314-5, eBook 978-3-319-25316-9, DOI 10.1007/978-3-319-25316-9; xiv, 270pp; hardback £99.99 [£74.99 on Amazon])

This is an academic book comprising 16 technical papers presented at a conference at Heidelberg University.

It began with individual collaborations among archaeologists, historians, geoscientists and computer experts at Heidelberg University, seeking to combine their different expertise, to address questions about past environments in combination with human actions and adaptations to them. In some ways these studies continue approaches pioneered from the late 1960s and 1970s among archaeologists, to not just 'add' scientific studies to their attempts to interpret the past, but also to integrate scientific approaches and apply cross-disciplinary methods in addressing archaeological questions.

When I was an Archaeology and Anthropology student at UC Berkeley 1968–72, there was increasing effort in the archaeological literature, especially in monograph reports, to integrate scientific studies of cultural archaeological and palaeoenvironmental evidence rather than simply to add appendices of reports on biological and environmental evidence. Through the late 20th and early 21st centuries interdisciplinary cooperation for archaeological goals has become de rigueur.

After an introductory, theoretical paper by the three editors, describing the interchange of ideas and methodologies among archaeologists, geoscientists and computer scientists, there follow four thematic 'Parts', each with several papers: altogether 15 further papers by 36 authors. The papers range from considerations of theory and method across a wide spectrum, spatially and chronologically, to more restricted cultural and time-confined studies.

Part I is 'Spatial analysis and geographical information systems'. Its papers explore theory and practice in interpreting perceived patterns in 'site catchment', 'point patterning', 'three-dimensional analysis' of built environments, and interpretations of 'material boundaries' in built space. Three papers are wide-ranging, citing specific examples as illustrations. Two others are site-specific: one on palaeoclimatic indicators in the Oder region from the Iron Age to the Middle Ages; and one on Megalithic graves distribution in Schleswig-Holstein.

Part II, 'Remote sensing and digital imaging analysis', describes methods of aerial data collection and the difficulties with its interpretation. The four papers comprise one more theoretical-methodological paper, two specific studies of application — one in northern Tanzania and one in the Sahara, and a third on practical application in assessing 'Cultural Heritage Documentation'.

Part III, 'Laser scanning applications', contains three papers on LiDAR, on 3D Laser Scanning of landscapes, and a site-specific study of laser scanning to detect and map Königstuhl Hillside in Heidelberg.

Part IV, 'Geophysical methods and data fusion', comprises three papers: two are wide-ranging papers on methods of data collection, and on interpreting 'fusion' between geophysical and geochemical data, and between surface and subsurface geodata; a third paper is a specific study using such approaches to interpret the prehistoric harbour at Akrotiri, Thera.

Each paper is referenced separately. There is a wealth of graphic, photographic and computer-generated interpretive figures throughout the book, mostly in full colour; and there is a short, but adequate general index.

Personally, I found three papers especially interesting: one on the use of remotely-sensed evidence to reconstruct palaeoenvironments in northern Tanzania, a 'cradle of humankind'; one searching for 'the optimal paths' of trans-Saharan trade routes; and the aforementioned geoarchaeological study of Late Bronze Age (Minoan) Akrotiri harbour.

As said, this is an academic book, sometimes heavy-going, but nevertheless fascinating in its explorations in what can be done when practitioners in these seemingly disparate academic disciplines combine efforts. Even as I read the book, volume 43 of the *Journal of Field Archaeology* arrived into my postbox, itself including two papers on the use of remote sensing of soil and Iron Age–medieval social geographic distribution patterns in southern India; and one on the use of LiDAR to find and interpret late prehistoric human settlement patterns in Santarém, Lower Amazon.

— David M. Jones, OUGS Proceedings Editor

Book review

Siegert, M. J., Jamieson, S. S. R., and White, D. A. (eds) 2018 *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. London: The Geological Society Special Publication 461 (ISBN 978-1-78620-322-9; v, 255pp; hardback, £100)

I thought that I had drawn a very short straw when left with the last book in the 'review' pile at the OUGS AGM last March: a collection of technical papers concerning the latest research in Antarctica. In fact, it proved to be absorbing, if at times challenging, reading.

As is usual with Geological Society Special Publications, a selection of peer-reviewed papers is grouped around a common theme — in this case an initiative by SCAR (the Scientific Committee on Antarctic Research) arising out of an international Horizon Scan to identify the most pressing questions regarding the future stability of Antarctica. 'Horizon Scan' is a term borrowed by the scientific community from government policy-makers and perhaps best summed up, if not necessarily followed, by our own UK government's Horizon Scan department, where they declare on their website a desire to prevent situations where "issues appear unexpectedly when with hindsight many were foreseeable".

Of the 80 questions from the original SCAR Horizon Scan at least 14 relate to subsurface processes, and here subsurface relates not only to the land beneath the ice (both onshore and offshore), but also to the internal structure of the ice itself. So the papers here are concerned with boundary conditions influencing subglacial topography, basal water, ice-sheet rheology (ice-flow rock deformation) and phenomena affecting ice-flow processes, for example ice-sheet structures and large stores of previously unknown groundwater. In addition, glacial sediments and formerly glaciated terrain can also inform about past ice-sheet dynamics.

After an introduction (open access) giving a historical perspective of Antarctic scientific exploration, and summarising the current state of Antarctic research, the lead editor offers a history of subsurface lake exploration (open access) and reveals the tensions between international collaboration and competition to be the first to drill into previously sealed Antarctic lakes, for example. There follow 15 papers describing research at various locations.

Dome A at over 4000m is the highest point of the central East Antarctic Ice Sheet (EAIS), and is the subject of three papers. Wang *et al.* (open access) use radar to discern the distinct crystal fabrics formed under increased glacial stress and how it modifies ice flow. Radio wave reflections are influenced by ice-crystal alignments and anisotropic variation here. Conventional ice-sheet flow modelling assumes isotropic properties, hence the importance of this distinction. Wrona *et al.* also use radar to reveal non-uniform ice deformation resulting in ice fingers. The Gamburtzev Mountain Range underneath Dome A appears to have been a nucleation site for ice for at least 14Ma; and Talalay *et al.* describe the first drilling methods proposed for this site.

The EAIS is potentially the largest source of sea level rise in the world and the Totten Glacier at its eastern edge is its largest outflow. Here, Roberts *et al.* (open access) use a combination of airborne radar, satellite data, and modelling to examine the effect of ocean heat on the variability of glacier movement and melt. Near by, at Law Dome, Goodwin *et al.* explore historical subglacial lake outburst events and their causes.

At the South Pole, Beem *et al.* address the anomaly of a subglacial lake with basal water in the vicinity of a cold bed. They conclude that historical ice flow, rather than geothermal activity, is the cause. A subsequent paper (not in this volume) reached the opposite conclusion and that led to recent headlines about a hotspot under the South Pole. Interestingly Martin Siegert, the lead editor of this volume, was involved in both papers.

On the Northern edge of the EAIS Swain uses an area devoid of ice (known as an oasis) to evaluate the geomorphological evolution of the area, while on the southern edge Pandey *et al.* use heavy minerals in marine sediments to identify their origin, and thus past East Antarctic Ice Sheet behaviour.

Lake Vostok is the largest subglacial lake so far discovered in Antarctica. Alekhina *et al.* describe the attempts to drill to Lake Vostok and the unfortunate use of kerosene as a drilling fluid, with the resulting contamination of the lake. Forsberg *et al.* describe new airborne gravity, magnetic and radar measurements around the coastline of the Weddell Sea to complete the gravity coverage of Antarctica. Further afield White *et al.* discuss what South Georgia's glacial sediments reveal about ice cover at the Last Glacial maximum and how this helps anticipate future marine ice sheets.

In West Antarctica, At the Institute Ice Stream (IIS) Jeofry *et al.* (open access) use airborne geophysics to reveal new details of embayments and grounding lines where the Ice Stream may be prone to ocean driven warming. Siegert *et al.* (open access) use data from the IIS to identify groundwater beneath the ice sheet bed and how it affects the macro flow of ice, while at the tip of the Antarctic peninsula Casas *et al.* offer new data to compare and contrast measurements of marine glacial fans and deduce climate and tectonic activity have been the main factors in large-scale instability.

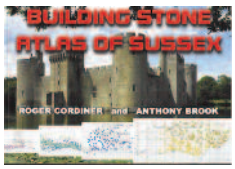
Finally van Wyk de Vries *et al.* (open access) look at the geophysical evidence for rifting and volcanism in West Antarctica and identify 138 volcanoes, 91 of which were not previously known. The lead author was still an undergraduate when he instigated this research.

Each paper includes comprehensive diagrams, charts and photographs and has its own reference list, and the book is fully indexed. There are a few minor editing errors I noticed. For example some, previously colour, figures are now in black and white and so their keys, referring to colour, are redundant. And some errors in titles in the reference lists make cross-referencing slightly more difficult than it should be.

One problem for me is the initial coat of the publication. At £100 I would not consider buying this for general reading, but of course the volume is not aimed at the casual reader. Being a collection of papers it is accessible through the usual academic channels (if you have the means) and, happily, as I have indicated, eight of the 17 papers are open access, that is, freely accessible on line, as are all the abstracts, via the Lyell Collection website of the Geological Society, or via Google Scholar for example.

— Phil Ridley, BSc Hons Geosciences (Open)

Book review



Cordiner, Roger, and Brooks, Anthony 2017 *Building Stone Atlas of Sussex*. Worthing: Roger Cordiner (ISBN 978-1-910719-49-7; 147pp; paperback £30 [available from the author: Roger Cordiner, 9, The Rowans, Grand Avenue, Worthing BN11 5AT, £30 plus £5 p&p)

This is an impressive volume summarising the use of natural stone at each of the parish churches in East and West Sussex. That Roger and Anthony visited every site (almost 350) is impressive in itself; that they did so using only public transport and their tireless legs we could have cause to stray into hyperbole.

The introduction tells us that, "This Atlas presents a comprehensive guide to the building stones used in West and East Sussex from *c.* 950 to 1840." Thereby, the book focuses on local Sussex stones, but also provides a helpful review of some other English stones and a few continental ones. The *Atlas* has been compiled from a detailed survey of 302 extant medieval parish churches, Chichester Cathedral, 14 ruined or lost churches and 5 ruined religious houses; 22 further churches bordering Sussex have also been included in the survey for 'enhanced coverage'.

The book is A4 landscape in format and beautifully presented in full colour with numerous maps, photographs and diagrams, and a helpful index of place names.

The opening pages provide a brief review of the local Sussex geology and the principal beds lending themselves to use as building stones, together with a historical summary starting with the Roman use of stone.

The remainder of the book (109 pages) provides a more systematic and detailed look at each of the building stones represented in Sussex churches, starting with those of the local Purbeck Beds and ending with the use of travertine (or tufa) from the Quaternary. For each stone the text addresses background geology, alternative names in the literature, historic use and the distribution of the stone in the context of the surveyed buildings in Sussex; the last element supported by a standardised county map (based on the Ordnance Survey National Grid), with coloured 2km squares to highlight local use underlain by the Formation (or stone type's) outcrop. Each stone is well illustrated as to the different varieties, or diagnostic features, to be seen and the range of uses the stone has traditionally been used for. These sections provide a thorough gazetteer of local building stones used in Sussex.

The *Atlas* also provides the same information for imported stones, both from other English sources and from the Continent. The authors have chosen to include monumental stones in their descriptions of building stones, which enabled them to include descriptions of materials less likely to be found in the church fabric, such as alabaster and Tournai Marble, but sometimes present in memorial fixtures. Two glossaries are provided, one architectural and the other geological. The latter is somewhat idiosyncratic in that it occasionally provides a definition of words explained elsewhere in the text, such as chalk, flint and Sarsen Stone (all chapter headings) but omits flaser-bedded, spherulitic siderite and lignite (all on page 16).

With such a large body of data collated to produce the *Atlas* it was important that some conclusions were drawn from the individual maps, and at various places in the texts the authors have identified patterns of distribution, notably along river valleys and stretches of coastline, and provided some helpful explanations for these patterns.

There is a wealth of information contained within this volume, which makes it a useful reference book for those with an interest in geology or historic buildings. In a county with so few natural rock exposures, this publication can be used to enhance field visits to Sussex, notably to see examples of some of the more unusual rock types such as Mixon Stone and Lavant Stone. It is, however, unfortunate that the authors have not fully exploited this aspect. Where grid squares contain two or more review sites, we do not know whether the stone is present at one site (which one?) or all sites. Indeed, as the list of churches in the Appendix does not give a grid reference, I had to cross-reference with another source to help identify the church(es) within the grid square.

While the standard of photography of individual stones is very good, it is often more instructive to see the stone itself and many readers may want to use the book as a guide when visiting the Sussex churches. I would therefore have liked to have seen more captions describing where a particular stone could be seen; too often the text states simply the name of the church, whereas an additional 'north chancel wall' (for example) would give the visitor a more reasonable chance of locating the stone.

These points aside the *Atlas* provides a welcome follow-up to *Building Stones of West Sussex* by Roger Birch and Roger Cordiner (2014), which is now out of print. The production values and information content of this volume, in the reviewer's opinion, justify the cost, and for anyone with an interest in Sussex geology the *Atlas* should provide a welcome addition to his or her library. Copies can be obtained from the lead author. Please enclose a cheque for £35 (to include p. and p.) made out to Mr. R. Cordiner and post to: Mr R. Cordiner, 9, The Rowans, Grand Avenue, Worthing, BN11 5AT

— Geoff Downer, BSc Hons (Open)

Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As *OUGS Proceedings* Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS AGM and Symposium, all OUGS members are grateful to you for presenting a lecture to us on your research, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the Symposium. As OU students and OUGS members we enjoy hearing and learning the information these events bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can identify and set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your article, it may be a good idea to send one with these items marked up or otherwise highlighted. I can accept electronic files attached to e-mails, text and image files on a CD or on a flash drive, or via shared media.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; as high a dpi as possible, please, for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as an AGM or Symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to publish with your article — again, usually 10 to 30 is only a rough guide.

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.
As the author, this responsibility is yours.

• Please do *not* embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustrations should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD or flash drive: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs. Alternatively, a digital sharing package can be used, such as Dropbox or similar.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a website), full title, periodical volume or number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3rd edn). Cambridge: Cambridge UP

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford UP

Please feel free to contact me at any time about your article:

Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
proceedings@ougs.org OR **ce.ocelotl@btinternet.com**

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Geologically inspired landscape, structure or feature in the British Isles, Winner — Duncan Woodcock
also, OUGS Popular Vote Winner
Devonian sandstones, South Ronaldsay, Orkney

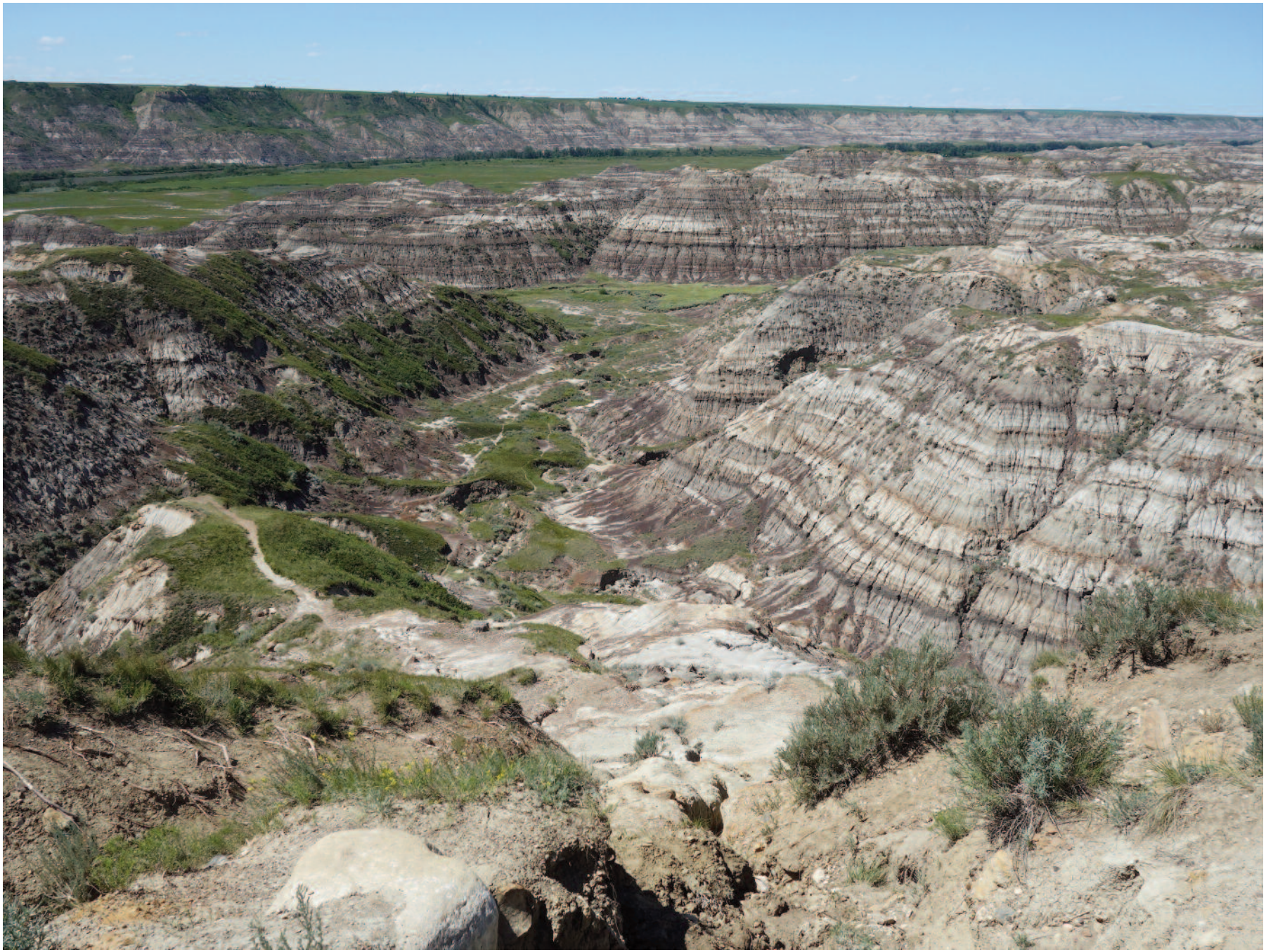
This dipping sequence of flaggy Devonian sandstones crops out along coastal cliffs at the south-east end of South Ronaldsay. The view is towards the east and approximately along strike; thus the cliff section gives a good indication of the true angle of dip towards the north.

Geologically inspired landscape, structure or feature, British Isles, Highly Commended — Jim Camp
Basalt pillow lavas at Clodgy Point, west Cornwall
This lava was erupted during the Middle Devonian (397–385Ma).

Geologically inspired landscape, structure or feature anywhere else in the world, Winner — Sandra Morgan

The Matterhorn (4,478m), showing three types of rock: foreground sedimentary, middle layer greenschist, upper layer gneiss

The Alpine orogeny began after the end of the closing of the Tethys Ocean, when the European plate collided with the Apulian plate, which itself had broken away from the African plate. The upper rock of the Matterhorn is gneiss that originated from the Apulian plate, hence the Matterhorn has been called an African mountain. Below the gneiss is greenschist formed from oceanic crust. The Matterhorn has four faces, which were eroded by ice over the past million years into their current pyramidal shape.



Geologically inspired landscape, structure or feature elsewhere in the world, Highly Commended — Ian Clarke *Upper Cretaceous sediments in the valley of the Red Deer River at Horsethief Canyon near Drumheller, Alberta*.

This is a typical 'Badlands' landscape and is a rich source of dinosaur fossils, many of which are on display at the nearby Royal Tyrrell Museum of Palaeontology. The sediments include beds of sandstone, siltstone, ironstone, coal and bentonite.

Industrial geology, Winner — Jim Camp
Wheal Owles Engine House, west Cornwall

Wheal Owles was the site of an infamous disaster in 1893. The mine was flooded when miners broke through into an adjacent unused shaft, which was already itself flooded. Nineteen men and one boy lost their lives. The purser, Captain Richard Boyns, was found guilty of negligence and fined £15.

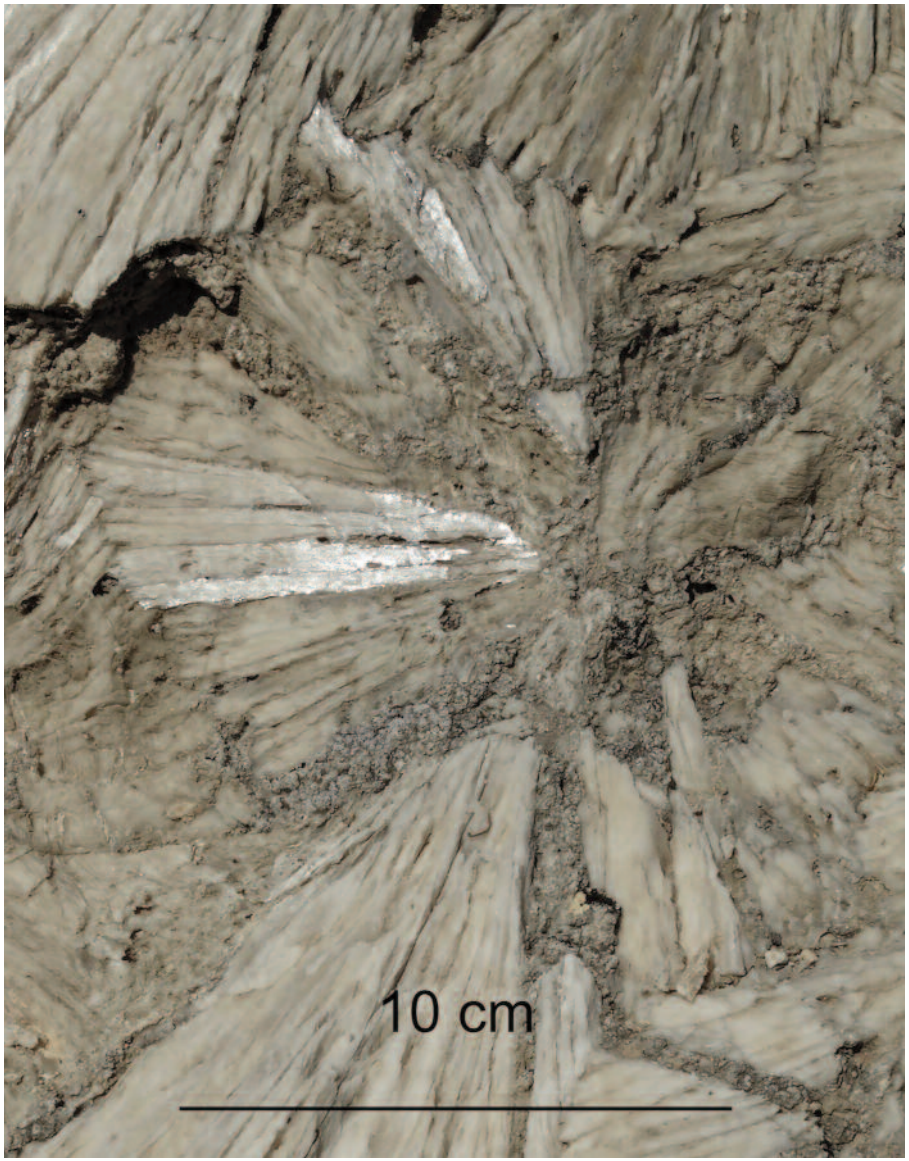
Industrial geology, Highly Commended — Stuart Swales

Graded grains make finer flour

Grading the raw material prior to crushing, Bulk Processing Trial at Cononish Gold Mine, nr Tyndrum

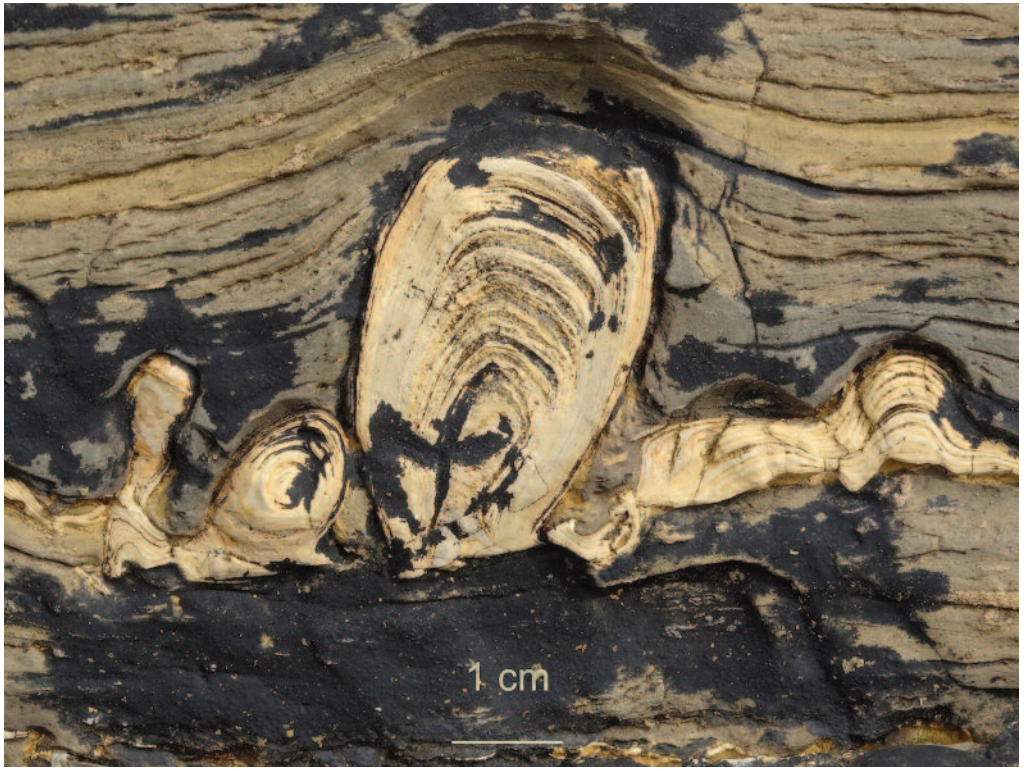
Mineral, rock or fossil specimen, or thin section/SEM view, Winner — David M. Jones
Fossil Rugose Coral, Far Arnside, Cumbria

Warm seas deposited marine sediments here *c.* 340–330Ma in the Early Carboniferous, which solidified into limestone. In 2000, a previously unknown coral bed was revealed when the River Kent channel shifted and eroded the salt marsh along the shore at Far Arnside, exposing the upper Dalton Limestone. Numerous specimens in the smooth limestone bedding can be seen in various orientations in astonishing detail. This photograph shows a longitudinal section of the Rugose solitary coral *Siphonophyllia* sp.



Gypsum 'rosette', Maroni, SE Cyprus

The radiating crystals of selenite in this gypsum 'rosette' can be seen in a small quarry on the outskirts of Maroni village, about 20km ENE of Lemesos. The evaporites exposed in this area belong to the Kalavasos Formation, a cyclical sequence of evaporites and marls produced by repeated evaporation and sedimentation within small basins during the Messinian Salinity Crisis.



Mineral, rock or fossil specimen, or thin section/SEM view, Highly Commended —Duncan Woodcock

Fossil stromatolites, Yesnaby, Orkney Mainland

The fossil stromatolites in this photograph are exposed in a small quarry at Yesnaby, on the west coast of Orkney Mainland. They were produced by mats of cyanobacteria that developed in a shallow water body during the early Devonian. Periodic covering of the mats by fine-grained sediment produced the prominent laminations visible in the photograph.